

NAVAL POSTGRADUATE SCHOOL Monterey, California





THESIS

A COMPUTATIONAL AND EXPERIMENTAL INVESTIGATION OF INCOMPRESSIBLE OSCILLATORY AIRFOIL FLOW AND FLUTTER PROBLEMS

by

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June, 1993

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by

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Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

In this thesis several incompressible oscillatory flow and flutter problems were investigated. First, a previously developed unsteady panel code was modified so that systematic comparisons with Theodorsen's classical theory could be accomplished. It was found that the panel code is in excellent agreement with the Theodorsen results. Second, the panel code was applied to the analysis of bending-torsion flutter. Again, general agreement with Theodorsen's flutter predictions was obtained. In the experimental part of the thesis two flow visualization experiments were performed. First, the vortical flow patterns generated by an airfoil executing harmonic plunge oscillations were visualized. In the second experiment, the interference effects between a stationary airfoil and a small vane executing plunge oscillations were explored.

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TABLE OF SYMBOLS

- a elastic axis position taken from the midchord
- **b** half chord
- C_{α} spring constant for pitch
- Ch spring constant for plunge
- C_n drag coefficient
- C_{t.} lift coefficient
- $C_{L\alpha}$ lift coefficient as a result of pitch
- $C_{\rm Lh}$ lift coefficient as a result of plunge
- C_{Mo} moment coefficient as a result of pitch
- $\mathbf{C}_{\mathbf{M}\mathbf{h}}$ moment coefficient as a result of plunge
- h plunge amplitude
- i denotes complex number
- I, mass moment of inertia
- $\mathbf{I}_{\mathbf{L}}$ denotes imaginary part of lift
- $\mathbf{I}_{\mathbf{M}}$ denotes imaginary part of moment
- Im Imaginary part
- $\mathbf{K}_{\mathbf{p}}$ reduced frequency used in panel code
- $\mathbf{K_t}$ reduced frequency used in Theodorsen analysis
- κ mass ratio $(1/\mu)$
- L lift force per unit span
- $\mathbf{L}_{lpha}, \mathbf{L}_{eta}, \mathbf{L}_{eta}$ aerodynamic coefficients used for Theodorsen analysis
- **M** moment
- $\mathbf{M_h}, \mathbf{M_\alpha}$ aerodynamic coefficients used for Theodorsen analysis
- q dynamic pressure

- Re real part
- R_{L} real part of lift
- R_M real part of moment
- S_{α} static moment about the elastic axis
- t nondimensional time
- U freestream velocity
- AOA angle of atack
- α pitch amplitude
- ρ density
- ϕ phase angle between force and motion
- $\phi_{\mathbf{L}\alpha}$ phase angle between lift force and pitch motion
- ϕ_{Lh} phase angle between lift force and plunge motion
- $\phi_{M_{N_{N}}}$ phase angle between moment and pitch motion
- ϕ_{Mh} phase angle between moment and plunge motion
- ω frequency of harmonic oscillation (rad/sec)
- ω_{lpha} natural frequency of system for pitch
- $\omega_{\mathbf{h}}$ natural frequency of system for plunge

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I. INTRODUCTION

A. GENERAL

In this thesis, several numerical methods were used to analyze the flow about an airfoil performing unsteady motion in an inviscid incompressible fluid. First, the unsteady motion of a single airfoil was analyzed after modifying the U2DIIF code [ref.2]. The primary purpose was to verify the code against the proven theory of Theodorsen for analyzing the phenomenon of flutter. To accomplish this the U2DIIF code was modified to calculate aerodynamic values over a range of reduced frequencies and then apply these values to the flutter analysis.

Next, the propulsive effects of a plunging airfoil were verified through experimental methods using a low speed plexiglas wind tunnel.

Finally, an exploratory test was conducted in the department's smoke tunnel to study the interaction between a plunging airfoil and a stationary large airfoil.

B. SCOPE

Chapter II contains the modification of the single airfoil U2DIIF code into the code UPOT.f and extensive verification of this code against results produced by Theodorsen. Chapter III describes the UPOT code and explains the modifications which

were added to solve the flutter determinant. In chapter IV the flow visualization experiment is described which was performed to study the vortical wake patterns produced by a plunging airfoil. In chapter V a second experiment is described which was performed to explore a plunging airfoil's potential for control of flow separation.

II. SINGLE AIRFOIL ANALYSIS

A. U2DIFF PANEL CODE

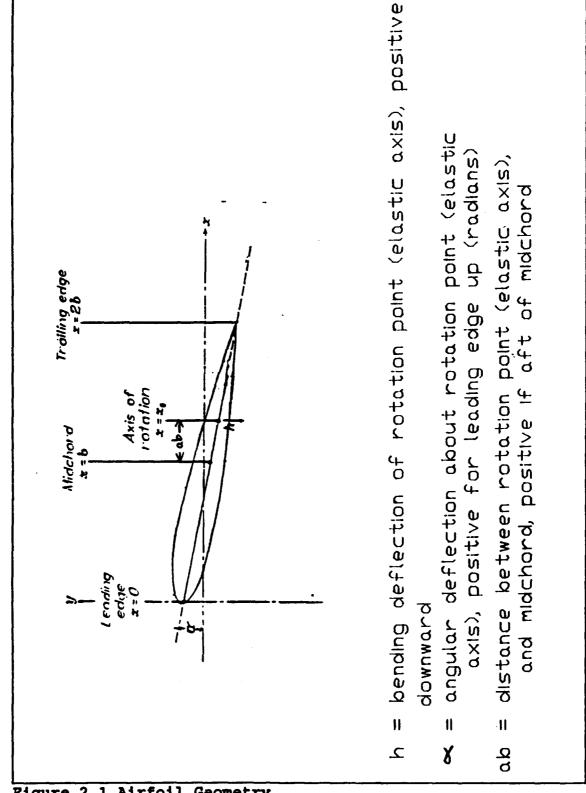
1. Geometry

Figure 2.1 shows a representation of the system that is analyzed using the panel code. Shown are the values for h (plunge) and α (AOA).

2. U2DIFF

The U2DIIF code was developed by TENG [ref.2] for the study of unsteady inviscid and incompressible flow over a single airfoil. The code is based on the extension of the panel method, developed by Hess & Smith [ref.4] for steady potential flow problems, to include the unsteady motion of the airfoil that is continuously shedding vortices into the trailing wake. This vortex shedding process is nonlinear in that the wake vortices influence the flow over the airfoil which in turn alters the vortex shedding as the airfoil proceeds in time.

The non-linearity of the unsteady flow makes this problem different from the steady flow problem which requires only simple Gaussian elimination. Teng developed a code that used an iterative type of solution. Typical program output includes the airfoil pressure distribution, force and moment coefficients, and the trailing vortex wake pattern. No



2.1 Airfoil Geometry

attempt is made here to reproduce the work of Teng or to explore the operation of the U2DIIF code, but the reader is encouraged to review reference 2.

B. PHASE PROGRAM

The phase program was put through some verification by Neace [ref.9] and modified slightly in order to present results for harmonic motion. The code PHV3.f (phaseshift) was written by Neace to convert the time dependent output of lift and moment histories to harmonic output using an iterative curve fit algorithm:

$$F(t) = Amp * Sin(\omega t + \phi)$$
 (2.1)

where Amp = amplitude of motion, ω = frequency, and ϕ = phase angle between motion and the aerodynamic forces. One primary output of this program was the values of phaseshift (ϕ) between the AOA and coefficients of lift (C_L) and moment (C_M) for the pitching airfoil and the phaseshift between the plunge value (h/2b) and the C_L and C_M for the plunging airfoil. The other output was the amplitude of C_L and C_M for the pitching or plunging case.

C. MODIFICATION OF U2DIIF AND PHASE PROGRAM

In an attempt to make the above mentioned codes more "user friendly", the two codes were combined into a single code named UPOT.f. The modification involved a new input file called UPOT.in which gives the user several options of operation. The input file can call for the analysis of steady flow only, straight and modified ramp motion, pitch oscillation, plunge oscillation, and the capability of performing the oscillation analysis over a series of reduced frequencies. A sample input file is shown in Figure (2.2).

1. Output

Outputs from the code have been limited to reduce the amount of computer space taken up by the code operation. A sample calculation was run using the input from Figure (2.2) and the on-screen output is shown in Figure (2.3). Of course, the user can modify the output portions of the code to minimize output. The following list describes the input/output files and the data they contain.

- a. UPOT.IN: The input file figure (2.2).
- b. CL.d: This file contains the various AOA values along with its corresponding C, for each time step.
- c. CM.D: This file contains the various AOA values along with its corresponding C_{μ} for each time step.
- d. PHASE.d: This file contains the values of non dimensional time (t), AOA, C_L , C_M , for each time step.
- e. FOR015.DAT: This file contains the values of non dimensional AOA, curve fit for $C_{\rm L}$, curve fit for $C_{\rm H}$, (used in the phase portion of program).
- f. CPSS.d: This file contains the steady state pressure coefficient for the mid point locations of all the air foil panels.
- g. CPU005.d: This file contains the unsteady pressure coefficient for the mid point location of all airfoil

- panels. (in this case the values are for an AOA equal to 5 degrees).
- h. PHZSWP.d: This file contains the phase information of the reduced frequency sweep portion for the program. The file contains the phase angle of $C_{\rm L}$, and $C_{\rm M}$, and the amplitude of $C_{\rm L}$, $C_{\rm M}$.
- i. FLUTTER.IN: This file contains information that can be used to solve the flutter determinant. It contains K_p , C_l Re, C_l Im, C_M Re, C_M Im for the pitch or plunge case.

```
stdin
                                                                                                                                          Page 1
      AIRFOIL TYPE: NACA 0012 AIRFOIL
NLOWER = 50 , NUPPER = 50
      IFLAG NLOWER NUPPER
                      50
                                  50
      AIRFOIL TYPE
      IRAMP
                 COSCIL
                               ALPI
                                                   ALPMAX
                                    -3.0
                                                     3.0
                                                                             0.37
                 REQSTP
                               REQENL
      FREQ
       . 68
                      0.01
      IGUST UGUST VGUST
      TTRANS DELHX DELHY DELI PHASE
O .00 .0 .0 0.00
CYCLE NTCYCLE TOL
    0 .00
CYCLE NTCYCLE
                                  0.005
      2 60 0.005
naot & naot X aga values multiplied by 10 (integer)
2 05 10 20 25 39 50
                    60
Comments...
IRAMP 0: n/a
                                             RFREQ is based on full chord
             1: Straight ramp
2: Modified ramp
                                              RFREQ is based on full chord
IOSCIL 0: n/a
             1: Sinusoidal pitch, motion starts at min Aoa
ITRANS 0: n/a
1: Translational harmonic oscillation
ALPI/ALPMAX Minimum/MAX AOA in degrees for IRAMP/ITRANS/IOSCIL
MAX does not apply for ITRANS

PIVOT Location of Elastic Axis as a fraction of full chord

FREQ Initial reduced frequency for program

RFOSTP Reduced freq step size for a sweep of freq.'s(enter 0.0 if only one calculation to desired)
lation is desired.)
RFQFNL Final freq for the sweep
REGENT Final freq for the sweep

DELHY
Translational amount in the vertical direction (dist/full chord)

DELHY
Max Translational amount in the vertical direction (h/fullchord(b))

DELI
Min Translational amount in the vertical direction (h/b)

CYCLE: $ of cycles for oscillatory motions

-In case of ramp, cycle=1.5 denotes airfoil is held
at max aoa for the duration of .5 cycle

-For steady state solution set it to 0
NTCYCLE: # of time steps for each cycle
CYCLE*NTCYCLE is limited to 200 currently.
TOL Tolerance for convergence of the unsteady solution. (recommend using not
       less than .001)
NAOT: $ of input aoa for cp output
- angles should be in increasing order,
- for oscilatory motions angles should increase
first, then decrease. Decreasing angles are for
                 the return cycle..
```

Figure 2.2 UPOT.IN

```
stdin
                                                                               Page 1
          AIRFOIL TYPE : NACA OO12 AIRFOIL
NLOWER = 50 , NUPPER = 50
  IFLAG (C:NACA, 1:INPUT) = NO. PANELS UPPER SURFACE = NO. PANELS LOWER SURFACE =
  OSCILLATORY MOTION, IOSCIL = INITIAL ANGLE OF ATTACK = -3.000C FINAL ANGLE OF ATTACK = 3.000C REDUCED FREQ. FOR OSCIL = C.680C REDUCED FREQ. STEP = 0.0100 FINAL REDUCED FREQ. = 0.7000
                              =
  PIVOT POINT
                                     0.3700
  TOTAL # OF CYCLES

• of TIME STEP5 PER CYCLE
TOLERANCE FOR CONVERGENCE
                              = 2.0000
                                      60
                                     0.0050
  FREQ SWEEP
FREQ = 0.680000
 STEADY FLOW SOLUTION AT ALPHA = -3.000000
       18
19
   20
   24
   33
   35
   36
37
```

Figure 2.3a UPOT output

				sto	lin	Page 2
39	0.125130	-0.890054	-0.086820	-0.589671	-1.26082	?
40				-0.632708		
41				-C.682121		
42				-0.740144		
43				-0.810000		
44				-0.896386		
45 46				-1.006151 -1.148872		
47				-1.334727		
48				-1.554189		
49	0.002465	0.075008	-0.086820	-1.656311	-1.629819	9
50	0.000493			-0.999986		
51	0.000493		-0.086820		-0.74181	
52	0.002465		-0.086820		-0.050689 0.35240	
53 54	0.006399		-0.086820 -0.086820		0.57020	
55	0.020090		-0.086820		0.69780	
56	0.029792		-0.086820		0.779380	
57	0.041349		-0.086820		0.83525	
58	0.054717		-0.086820		0.87554	
59	0.069841		-0.086820		0.90571	
60 41	0.086664		-0.086820		0.92893	
61 62	0.105117		-0.086820 -0.086820		0.94713	
63	0.146621		-0.086820		0.97311	
64	0.169507		-0.086820		0.98232	
65	0.193698		-0.086820		0.98966	4
66	0.219097		-0.086820		0.99544	
67	0.245605		-0.086820		0.99992	
68 69	0.273117			-0.006640 -0.011593	1.003314	
70	0.330715			-0.014984	1.00746	
71	0.360573			-0.017049	1.00848	
72	0.390982			-0.017994	1.00895	
73	0.421821			-0.018001	1.00896	
74	0.452969			-0.017221	1.00857	
75	0.484302			-0.015784	1.00786	
76 7.7	0.515698			-0.013805 -0.011369	1.00566	
78	0,578179			-0.00B545	1.00426	
79	0.609018			-0.005387	1.00269	
80	0.639427			-0.001926	1.00096	
81	0.669285		-0.086820		0.99908	
82	0.698476		-0.086820		0.99706	
83 84	0.726883		-0.086820 -0.086820		0.99254	
85	0.780903		-0.086820		0.99001	
86	0.806302		-0.086820		0.98725	
87	0.830493	0.894605	-0.086820	0.031258	0.98424	
88	0.853379		-0.086820		0.98094	
89	0.874870		-0.086820		0.97730	
90	0.894883		-0.086820 -0.086820		0.97325	
91 92	0.930159		-0.086820		0.96872	
93	0.945283		-0.086820		0.95782	
94	0.958651		-0.086820		0.95114	
95	0.970208	0.921351	-0.086820	0.110175	0.94330	6
96	0.979910		-0.086820		0.93390	
97	0.987718		-0.086820		0.92219	
98 99	0.993600		-0.086820 -0.086820		0.90680 0.88464	
100	0.999507		-0.086820			

****	BEGIN UNS	TEADY FLOW	SOLUTION	****		
ist	ep alpha	time	nitr	cl, cd	, cm	
1	-3.0000	0.0000	1	-0.3479	0.0002	-0.0403
2	-2.9836		ô		-0.0005	-0.0424
3	-2.9344		0	-0.3247	-0.0012	-0.0434
4	-2.8532		0	-0.3101	-0.0019	-0.0441

Figure 2.3b UPOT output

				S	tdin		. Programa Terror No.	Page 3
5	-2.7406	0.6160	0	-0.2935	-0.0027	-0.0444		
6 7	-2.5981	0.7700	0000000	-0.2751 -0.25 49	-0.0033 -0.0039	-0.0444 -0.0441		
é	-2.4271 -2.2294	0.9240 1.0780	č	-0.2332	-0.0044	-0.C434		
9	-2.0074	1.2320	Ç	-0.2101	-0.0047	-0.0424		
10	-1.7634 -1.5000	1.3860 1.5400	9	-0.1858 -0.1605	-0.0048 -0.0048	-0.0410 -0.0393		
12	-1.2202	1.6940	č	-0.1345	-0.0046	-0.0373		
13	-0.9271	1.8480	0	-0.1080	-0.0043	-0.0350		
14	-0.6237 -0.3136	2.0020 2.1560	0	-0.0812 -0.0545	-0.0038 -0.0031	-0.0323 -0.0295		
16	0.0000	2.3100	0,40000,40000,400	-0.0280	-0.0023	-0.0264		
17 18	0.3136	2.4640 2.6180	Ş	-0.0021 0.0230	-0.0014 -0.0004	-0.0231 -0.0197		
19	0.9271	2.7720	č	0.0471	0.0006	-0.0161		
20	1.2202	2.9260	C	0.0699	0.0016	-0.0124		
21 22	1.5000	3.0800 3.2340	:	0.0911 0.1107	0.0025 0.0034	-0.0087 -0.0050		
23	2.0074	3.3880	č	0.1284	0.0042	-0.0013		
24	2.2294	3.5420	3	0.1440	0.0048	0.0024		ļ
25 26	2.4271 2.5981	3.6960 3.8500		0.1573 0.1683	0.0053 0.0056	0.0059 0.0093		
27	2.7406	4.0040	ċ	0.1769	0.0057	0.0126		i
28	2.8532	4.1590	õ	0.1829 0.1863	0.0056 0.0054	0.0156		
29 30	2.9836	4.3120 4.4660	č	0.1872	0.0050	0.0184 0.0210		
31	3.0000	4.6200	0 0 0	0.1855	0.0045	0.0232		
32 33	2.9836	4.7740 4.9280	0	0.1812	0.0038 0.0031	0.0252 0.0268		
34	2.8532	5.0820	č	0.1653	0.0024	0.0280		
35	2.7406	5.2360	1	0.1538	0.0016	0.0289		
36 37	2.5981 2.4270	5.3900 5.5440	0	0.1402 0.1246	0.0008 0.0002	0.0295 0.0296		
30	2.2294	5.6980	C	0.1071	-0.0004	0.0294		
39	2.0074	5.8520	C	0.0880 0.0676	-0.0009	0.0288 0.0278		
40 41	1.7634	6.0060 6.1600	5	0.0459	-0.0012 -0.0014	0.0265		
42	1.2202	6.3140	0	0.0234	-0,0014	0.0249		
43	0.9270 0.6237	6.4680 6.62-20	0	0.0001 -0.0235	-0.0013 -0.0010	0.0229 0.0206		
45	0.3136	6.7760	C	-0.0472	-0.0006	0.0181		
46	0.0000	6.9300	1	-0.0709	0.0000	0.0153		
47	-0.3136 -0.6237	7.0840 7.2380	0	-0.0941 -0.1166	0.0006 0.0014	0.0123 0.0092		
49	-0.9271	7.3920	0	-0.1382	0.0021	0.0059		
50	-1.2202	7.5460	0	-0.1586	0.0028 0.0035	0.0025 ~0.0010		ï
51 52	-1.5000 -1.7634	7.700C 7.8540	l C	-0.1776 -0.1950	0.0041	-0.0015		
53	-2.0074	8.0080	0	-0.2105	0.0047	-0.0080		
54 55	-2.2294 -2.4271	8.1620 8.3160	0	-0.2241 -0.2356	0.0051 0.0053	-0.0114 -0.0147		
56	-2.5981	8.4700	Ö	-0.2448	0.0054	-0.0179		
57	-2.7406	8.6240	1	-0.2516	0.0053	-0.0210		
58 59	-2.8532 -2.9344	8.7780 8.9320	0	-0.2559 -0.2578	0.0051 0.0047	-0.0239 -0.0265		
60	-2.9836	9.0860	0	-0.2571	0.0042	-0.0289		
61	-3.0000	9.2400	0	-0.2539 -0.2482	0.0035	-0.0309 -0.0327		
62 63	-2.9836 -2.9344	9.3940 9.5480	0	-0.2482	0.0028 0.0020	-0.0327 -0.0342		
64	-2.8532	9.7020	0	-0.2295	0.0011	-0.0353		i
65 66	-2.7406 -2.5981	9.8560 10.0100	0	-0.2168 -0.2019	0.0003 -0.0005	-0.0360 -0.0364		
67	-2.4271	10.1640	ő	-0.1851	-0.0012	-0.0365		
68	~2.2294	10.3180	0	-0.1664	-0.0017	-0.0361		
69 70		10.4720 10.6260	0	-0.1463 -0.1247	-0.0022 -0.0025	-0.0354 -0.0343		
71	-1.5000	10,7800	0	-0.1020	-0.0026	-0.0329		
72		10.9340	0	-0.0784	-0.0026 -0.0024	-0.0311		
73		11.0880 11.2420	0	-0.0542 -0.0296	-0.0020	-0.0290 -0.0267		
75	-0.3136	11.3960	0	-0.0050	-0.0015	-0.0240		
76		11.5500 11.7040	0	0.0195 0.0436	-0.0008 -0.0001	-0.0211 -0.01 8 1		
L	0.3136	-1		0.0430	3.0001			

Figure 2.3c UPOT output

```
stdin
                                                                                                     ifi yezi
                                                                                                                                           Page 4
                0.6237 11.8580
                                                                  0.0670
                                                                                    0.0007
                                                                                                     -0.0148
                0.9270 12.0120
1.2202 12.1660
                                                   0
                                                                  0.0894
                                                                                    0.0016
                                                                                                    -0.0114
-0.0079
     9C
8:
                                                                 0.1304
0.1486
0.1649
0.1792
                             12.3200
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                 1,5000
                                                                                    0.0033
                                                                                                     -0.0044
                1.7633 12.4740
2.0074 12.6280
2.2294 12.7820
      82
                                                                                    0.0040
                                                                                                     -0.0008
      8 3
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                                                                                    0.0046
                                                                                                      0.0028
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                                                                                                      0.0063
                                                                                    0.0051
                2.4270 12.9360
2.5981 13.0900
2.7406 13.2440
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      87
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                                                                                                      0.0161
                2.8532 13.3980
2.9344 13.5520
                                                                 0.2137
0.2161
      88
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                                                                                    0.0056
                                                                                                      0.0191
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      90
                2.9836 13.7060
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                                                                 0.2160
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                                                                                                      0.0242
     91
92
                                                  ō
                3.0000 13.8600
                                                                                    0.0042
                2.9836 14.0140
2.9344 14.1680
                                                                 0.2083
                                                   0
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                                                                                    0.0028
                                                                                                      0.0297
     94
95
                2.8532 14.3220
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                                                                                    0.0020
                                                                                                      0.0309
                2.1406 14.4760
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     96
97
                2.5981 14.6300
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                                                                                                      0.0321
                2.4271 14.7840
2.2294 14.9380
                                                                 0.1478
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-0.0008
                                                                                                      0.0322
                                                   0
      98
      99
                2.0074 15.0920
1.7634 15.2460
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                                                                 0.1100
                                                                                  -0.0013
-0.0016
                                                                                                      0.0312
   100
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                1.5000 15.4000
                                                                 0.0666
                                                                                                      0.0288
                                                  0
                                                                                  -0.0017
    102
                                                                                   -0.0017
                0.9271 15.7080
0.6238 15.8620
                                                                0.0197
    1 C 3
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    104
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               0.3136 16.0160
0.0000 16.1700
    105
                                                   ٥
                                                                -0.0287
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                                                                                                      0.0202
                                                  0
    106
                                                                -0.0528
                                                                                  -0.0002
0.0005
                                                                                                      0.0173
    107
              -0.3136 16.3239
-0.6237 16.4779
                                                               -0.0765
-0.0994
                                                                                                      0.0143
    108
                                                                                    0.0012
                                                                                                      0.0111
             -0.6237 16.4779
-0.9270 16.6319
-1.2202 16.7859
-1.5000 16.9399
-1.7633 17.0939
-2.0074 17.2479
                                                  0000
    109
                                                                -0.1215
                                                                                    0.0020
                                                                                                      0.0078
                                                               -0.1423
-0.1617
-0.1795
-0.1955
    110
                                                                                   0.0028
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    111
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   112
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                                                                                                     -0.0027
                                                                                                     -0.0063
                                                               -0.2095
-0.2212
-0.2308
-0.2379
              -2.2294 17.4019
-2.4270 17.5559
   114
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                                                                                    0.0052
                                                                                                    -0.0097
                                                                                                    -0.0131
              -2.5981 17.7099
-2.7406 17.8639
    116
                                                  00
                                                                                    0.0056
                                                                                                     -0.0164
                                                                                    0.0055
                                                                                                    -0.0195
   118
              -2.8532 18.0179
-2.9344 18.1719
                                                   1
                                                               -0.2426
-0.2447
                                                                                    0.0053
                                                                                                    -0.0224
                                                                                    0.0049
                                                                                                    -0.0250
              -2.9836 18.3259
                                                                -0.2444
                                                                                                     -0.0274
                              PHASE SHIFT ANALYSIS
FREQ = 0.6800000
 AMPLITUDE; clamp, cmamp : 0.2304234 3.4331881E-02
PHASE; clp, cmp : 184.9092 -37.54200
AVERAGE DRAG, TOTAL DRAG : 1.5421067E-03 9.4068512E-02
ETAS, WBAR : -0.2168084 -7.1127615E-03
FREQ SWEEP
FREO =
              0.690000
 STEADY FLOW SOLUTION AT ALPHA = -3.000000
            0.999507 -1.116717 -0.086820 0.280753 -0.848084
           0.997507 -1.116717 -0.086820

0.997535 -1.108171 -0.086820

0.993600 -1.100064 -0.086820

0.987718 -1.092523 -0.086820

0.979910 -1.085444 -0.086820

0.970208 -1.078820 -0.086820

0.958651 -1.072610 -0.086820

0.945283 -1.066794 -0.086820
                                                                 0.280753 -0.848084
0.213074 -0.887088
0.168200 -0.912031
0.134381 -0.930386
0.106525 -0.945238
0.082353 -0.957939
                                                                  0.060678 -0.969186
0.040815 -0.979380
           0.930159 -1.061323 -0.086820 0.022307 -0.988783 0.913336 -1.056157 -0.086820 0.002307 -0.986783 0.913336 -1.051250 -0.086820 -0.001780 -1.005873 0.874870 -1.046545 -0.086820 -0.027772 -1.013791
```

Figure 2.3d UPOT output

			sto	lin	Page 5
13	0.853379	-1.041994 -0.086820	-0.043274	-1.021408	
14		-1.037547 -0.086820			
15		-1.033154 -0.086820			
16		-1.028773 -0.086820			
17		-1.024362 -0.086820			
18		-1.019887 -0.086820			
19 20		-1.015315 -0.086820 -1.010628 -0.086820			
21		-1.005803 -0.086820			
22		-1.000836 -0.086820			
23		-0.995714 -0.086820			
24		-0.990441 -0.086820			
25		-0.985017 -0.086820			
26 27		-0.979449 -0.086820 -0.973745 -0.086820			
28		-0.967910 -0.086820			
29		-0.961956 -0.086820			
30		-0.955883 -C.086820			
31		-0.949692 -0.086820			
32		-0.943373 -0.086820			
33		-0.936907 -0.086820			
34 35		-0.930250 -0.086820			
36		-0.923337 -0.086820 -0.916066 -0.086820			
37	0.169507	-0.908273 -0.086820	-0.516866	-1.231611	
38		-0.899722 -0.086820			
39		-0.890054 -0.086820			
40		-0.878738 -0.086820			
41		-0.864972 -0.086820			
42 43		-0.847530 -0.086820 -0.824472 -0.086820			
44		-0.792611 -0.086820			
45		-0.746398 -0.086820			
46	0.020090	-0.675433 -0.086820	-1.148872	-1.465903	
47		-0.558323 -0.086820			
48		-0.346398 -0.086820			
49 50	0.002465	0.075008 -0.086820 0.854855 -0.086820			
51	0.000493	1.561213 -0.086820		-0.741819	
52	0.002465	1.669507 -0.086820		-0.050689	
53	0.006399	1.558290 -0.086820			
54	0.012282	1.445845 -0.086820			
55	0.020090	1.357269 -0.086820			
56 57	0.029792	1.287651 -0.086820 1.231267 -0.086820			
58	0.054717	1.184229 -0.086820			
59	0.069841	1.144055 -0.086820			
60	0.086664	1.109153 -0.086820			
61	0.105117	1.078474 -0.086820			
62	0.125130	1.051316 -0.086820			
63 64	0.146621 0.169507	1.027193 -0.086820 1.005756 -0.086820			
65	0.193698	0.986749 -0.086820		0.989664	
66	0.219097	0.969966 -0.086820		0.995444	
67	0.245605	0.955241 -0.086820			
68	0.273117	0.942428 -0.086820			
69	0.301524	0.931390 -0.086820			
70 71	0.330715	0.921993 -0.086820			
71 72	0.360573	0.914106 -0.086820 0.907597 -0.086820			
73	0.421821	0.902331 -0.086820		1.008960	
74	0.452969	0.898173 -0.086820		1.008574	
75	0.484302	0.894989 -0.086820	-0.015784	1.007861	
76	0.515698	0.892645 -0.086820		1.006879	
77	0.547031	0.891016 -0.086820		1.005668	
78 79	0.578179 0.609018	0.889982 -0.086820 0.889434 -0.086820		1.004263 1.002690	
80	0.639427	0.889276 -0.086820			
81	0.669285	0.889426 -0.086820		0.999089	
82	0.698476	0.889824 -0.086820	0.005855	0.997068	
83	0.726883	0.890423 -0.086820			
84 85	0.754395	0.891196 -0.086820 0.892138 -0.086820	0.014851 0.019880	0.992547 0.990010	
63	J. 130703		~.~.,000	2.770010	

Figure 2.3e UPOT output

<u> </u>				tdin		Page 6
0.806302	0.893264	-0.08682	0 0.0253	28 0.9872	55	
0.830493			0.0312	58 0.9842		
0.853379	0.896208	9 -0.08682	0 0.0377	45 0.9809	46	
0.874870	0.898136	-0.08682				
0.894883	0.900467	7 -0.08682	0 0.0527	75 0.9732	55	
	0.903280	0.08682	0.0615	67 0.9687	28	
0.930159	0.906679	-0.08682	0 0.0714	17 0.9636	30	
0.945283	0.910746	-0.08682	0 0.0825	65 0.9578	28	
0.958651					41	
					06	
0.999507						
BEGIN UNST	EADY FLOW	SOLUTION	****			
••••••	••••••	*******	* * * * * *			
ep alpha	time	nitr	cl,	cd, cm		
-3.0000	0.0000	1	-0.3479	0.0002	-0.0403	
-2.9836	0.1518	ô				
-2.9344	0.3035	ŏ	-0.3243	-0.0012		
-2.8532	0.4553	0				
-2.7406	0.6071	0	-0.2929	-0.0027	-0.0445	
-2.5981	0.7588	o o	-0.2744	-0.0034	-0.0446	
					-0.0442	
		Ō				
0.0000	2.2765	1	-0.0271			
0.3136	2.4283	0	-0.0012	-0.0014	-0.0234	
0.6237	2.5801	0	0.0238	-0.0004	-0.0199	
	2.7318	0	0.0478	0.0006	-0.0164	
		ò				
2.8532	4.0977	ō	0.1822	0.0056	0.0155	
2.9344	4.2495	Ō	0.1855	0.0054	0.0183	
2.9836	4.4013	0	0.1862	0.0050	0.0209	
3.0000	4.5530	0	0.1843	0.0045	0.0231	
2.9836	4.7048	0	0.1799	0.0038	0.0251	
				0.0031	0.0267	
1.5000		ŏ	0.0437	-0.0014	0.0266	
1.2202	6.2225	ŏ	0.0211	-0.0014		
0.9271	6.3742	Ö	-0.0021	-0.0013	0.0230	
0.6237	6.5260	ō	-0.0257	-0.0010	0.0207	
0.3136	6.6778	0	-0.0494	-0.0006	0.0182	
0.0000	6.8295	1	-0.0729	0.0000	0.0154	
-0.3136	6.9813	0		0.0007	0.0125	
-0.9270 -1.2202	7.4366	0	-0.1399 -0.1602	0.0021	0.0060 0.0026	
	0.830493 0.853379 0.874870 0.894883 0.913336 0.958651 0.970208 0.9779910 0.987713 0.997535 0.999507 BEGIN UNST B	0.830493	0.830493	0.806302	0.806302	0.806302

Figure 2.3f UPOT output

				S	tdin		Page 7
52	-1.7634	7.7402	о с	~0.1963	0.0042	-0.0044	
53	-2.0074	7.8919	Ō	-0.2117	0.0047	-0.0079	
54	-2.2294	8.0437	0	~0.2251	0.0051	-0.0113	
55	-2.4270	8.1955	Э	~0.2364	0.0053	-0.0147	
56	-2.5981	8.3472	1	-0.2454	0.0054	-0.0179	
57	-2.7406	8.4990	С	-0.2520	0.0053	-0.0210	
58	-2.8532	8.6508	0	-0.2562	0.0051	-0.0238	
59	-2.9344	8.8025	С	-0.2578	0.0047	-0.0265	
60	-2.9836	8.9543	0	-0.2570	0.0042	-0.0289	
61	-3.0000	9.1061	0	-0.2536	0.0035	-0.0310	
62	-2.9836	9.2578	C	-0.2477	0.0028	-0.0328	
63	-2.9344	9.4096	õ	-0.2394	0.0019	-0.0342	
64	-2.8532	9.5614	0	-0.2288	0.0011	-0.0354	
65	-2.7406	9.7131	0	-0.2159	0.0003	-0.036;	
66	-2.5981 -2.4271	9.8649	0	-0.2009	-0.0005	-0.0365	
67 68	-2.2294	10.0167		-0.1839 -0.1652	-0.0012 -0.0018	-0.0366 -0.0362	
69		10.1684	000	-0.1450	-0.0012	-0.0355	
70	-1.7634	10.4720	č	-0.1233	-0.0025	-0.0345	
71		10.6237	õ	-0.1006	-0.0027	-0.0330	
72		10.7755	õ	-3.0770	-0.0026	-0.0313	
73	-0.927	10.9273	č	-0.0528	-0.0024	-0.0292	
74		11.0790	Ö	-0.0282	-0.0020	-0.0269	
75		11.2308	ō	-0.0036	-0.0015	-0,0242	
76		11.3826	ō	0.0209	-0.0008	-0.0213	
77	0.3136	11.5343	00000	0.0448	-0.0001	-0.0183	
78	0.6237		C	0.0681	0.0007	-0.0150	
79	0.9270	11.8379	0	0.0904	0.0016	-0.0116	
80	1.2202	11.9897	С	0.1115	0.0025	-0.3081	
81	1.5000	12.1414	1	0.1311	0.0033	-0.0045	
82		12.2932	0	0.1493	0.0040	-0.0010	
83		12.4450	0	0.1654	0.0047	0.0026	
84		12,5967	0	0.1796	0.0052	0.0061	
85		12.7485	0	0.1915	0.0055	0.0095	
86		12.9003	1	0.2012	0.0057	0.0129	
87		13.0520	0	0.2085	0.0058	0.0160	
88		13.2038	C	0.2133	0.0056	0.0189	
89		13.3556	C	0.2156	0.0053	0.0217	
90		13.5073	C	0.2153	0.0048	0.0241	
91 92		13.6591 13.8109	ŏ	0.2125 0.2072	0.0042	0.0263 0.0282	
93		13.9626	ŏ	0.1995	0.0028	0.0297	
94		14.1144	ŏ	0.1894	0.0020	0.0309	
95		14.2662	ŏ	0.1770	0.0012	0.0317	
96		14.4179	ì	0.1625	0.0005	0.0322	
97		14.5697	Ó	0.1461	-0.0002	0.0323	
98		14.7215	0	0.1279	-0.0008	0.0320	
99		14.8732	0	0.1081	-0.0013	0.0313	
100		15.0250	0	0.0870	-0.0016	0.0303	
101		15.1768	٥	0.0647	-0.0018	0.0289	
102	1.2202	15.3285	Ç	0.0415	-0.0018	0.0272	
103		15.4803	0	0.0178	-0.0016	0.0252	
104		15.6321	0	-0.0063	-0.0013	0.0229	
105		15.7838	0	-0.0305	-0.0008	0.0203	
106		15.9356	1	-0.0546	-0.0002	0.0175	
107		16.0874	0	-0.0782	0.0005	0.0145	
108		16.2391	Ö	-0.1011	0.0012	0.0113	
109		16.3909	0	-0.1230	0.0020	0.0079	
110		16.5427	ó	-0.1437	0.0028	0.0044	
111		16.6945	1	-0.1630	0.0035	0.0009	
112		16.8462	0	-0.1807	0.0042	-0.0026	
113		16.9980	0	-0.1965	0.0048	-0.0061	
114		17.1498 17.3015	0	-0.2103 -0.2219	0.0052 0.0055	-0.0096 -0.0130	
115		17.4533	1	-0.2312	0.0056	-0.0130	
116		17.6051	ó	-0.2312	0.0055	-0.0163	
117 118		17.7568	Č	-0.2427	0.0053	-0.6 23	
118		17.9086	0	-0.2446	0.0049	-0.0250	
120		18.0604	Č	-0.2441	0.0044	-0.0274	
120	2.7030	.0.0007	J	4.2741	0.0074	0.02/7	
		PHASE SH FREQ =		ALYSIS 00000			

Figure 2.3g UPOT output

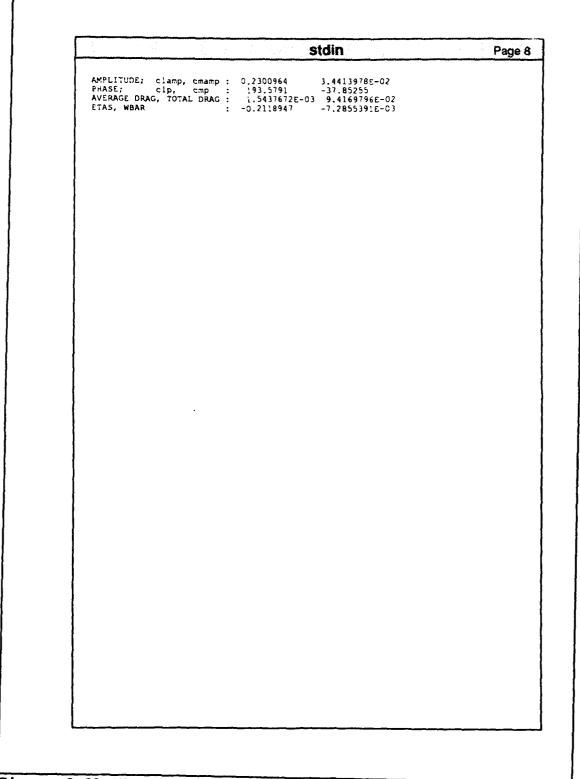


Figure 2.3h UPOT output

2. Difference Between UPOT and U2DIIF/Phase

The input file format was changed along with the following:

- The program can now analyze a pitch, plunge or ramp motion that starts from any minimum value of Alpha or plunge (h/2b). Previously, the program only accepted the initial position of zero. This program does not need to go through the origin.
- ullet The phase portion of the program was changed to curve fit $C_{\text{I.}}$ and C_{M} to a cosine function:

$$F(t) = Amp * Cos(\omega t + \phi)$$
 (2.2)

where, Amp = amplitude of motion, ω = frequency of motion, ϕ = phase angle between motion and the aerodynamic forces. This was done since the alpha and plunge values were allowed to start from a new zero position.

• The phase portion uses the middle 180 degrees of the final 360 degree cycle specified in the UPOT.in file. This change was done to capture an all positive area of the cosine curve for phasing analysis. The program integrates this portion of the cosine curve, and for proper code operation the area under the curve must be kept to one sign. If the areas of integration were chosen to include both sides of the axis, then the code would produce errors near 90 and 270 degrees.

3. UPOT Verification

The code UPOT did not incorporate any drastic changes to the prior codes, but the original code had never been extensively compared to prior theories over a wide range of reduced frequencies. When conducting these comparisons, it is easy to become confused. This section will go through the comparisons slowly to help alleviate that problem.

a. K_{panel} (K_p) vs. $K_{Theodorson}(K_t)$.

The equation for reduced frequency is:

$$K_p = \frac{\omega 2b}{U} \qquad K_t = \frac{\omega b}{U} \tag{2.3}$$

where: $\omega = \text{frequency of oscillation (rad/sec)}$

b = half chord (units to match U)

U =free stream velocity (units to match b).

The difference between K_p and K_t lies in the fact that K_p calls for the full chord and K_t calls for the half chord, hence, it is important to remember that K_p is twice K_t .

b. Aerodynamic Forces

The aerodynamic forces problem of simple harmonic motion about an equilibrium position was solved theoretically by Theodorsen in NACA TR-496 [ref.10] and outlined by Fung in [ref.5]. The complex equations were simplified using the simple harmonic motion equation and resulted in the following:

$$L = \pi \rho b^3 \omega^2 \left(L_h \frac{h}{b} + \left[L_\alpha - \left(\frac{1}{2} + a \right) L_h \right] \alpha + \left[L_\beta - \left(c - e \right) L_z \right] \beta \right) e^{i \left(\omega t + \phi_L \right)}$$
 (2.4)

$$M = \pi \rho b^{4} \omega^{2} \left(\left[M_{h} - \left(\frac{1}{2} + a \right) L_{h} \right] \frac{h}{b} + \left[M_{\alpha} - \left(\frac{1}{2} + a \right) \left(L_{\alpha} + M_{h} \right) + \left(\frac{1}{2} + a \right)^{2} L_{h} \right] \alpha$$

$$+ \left[M_{\beta} - \left(\frac{1}{2} + a \right) L_{\beta} - \left(c - e \right) M_{z} + \left(c - e \right) \left(\frac{1}{2} + a \right) L_{z} \right] \beta \right) e^{i \left(\omega t + \phi_{M} \right)}$$

$$(2.5)$$

L, M are the lift and moment per unit span of the airfoil about the elastic axis, b, h/b, a and α (radians), are

shown in Figure (2.1)., L_h , L_α , L_β , and M_α are defined by Scanlan [ref.6,pp.412-424] for various values of K_t and e. This analysis will not cover airfoil aileron combinations. Therefore β becomes zero and equations 2.4 and 2.5 reduce to:

$$L = \pi \rho b^3 \omega^2 \left(L_h \frac{h}{b} + \left[L_\alpha - \left(\frac{1}{2} + a \right) L_h \right] \alpha \right) e^{i(\omega t + \phi_L)}$$
 (2.6)

$$M = \pi \rho b^{4} \omega^{2} \left(\left[M_{h} - \left(\frac{1}{2} + a \right) L_{h} \right] \frac{h}{b} + \left[M_{\alpha} - \left(\frac{1}{2} + a \right) \left(L_{\alpha} + M_{h} \right) + \left(\frac{1}{2} + a \right)^{2} L_{h} \right] \alpha \right) e^{i \left(\omega t + \phi_{L} \right)}$$
(2.7)

The UPOT panel code used the following equations in defining lift and moment:

$$C_L = \frac{L}{2qb} = \sqrt{R_L^2 + I_L^2} e^{i(\omega t + \phi L)}$$
 $\phi_L = \tan^{-1} \frac{I_L}{R_L}$ (2.8)

$$C_{M} = \frac{M}{4qb^{2}} = \sqrt{R_{m}^{2} + I_{m}^{2}} e^{i(\omega t + \phi m)} \qquad \phi_{m} = \tan^{-1} \frac{I_{m}}{R_{m}}$$
 (2.9)

where R_L and I_L are the real and imaginary parts of C_L , and R_M and I_M are the real and imaginary parts of C_M . For the same conditions the lift (L) and moment (M) should be the same for both the panel code and Theodorsen. This fact allows for comparison of the magnitude, real, imaginary and phase of lift and moment.

For lift:
$$L_t$$
 (eqn 2.6) equals L_p (eqn 2.8)

$$\pi \rho b^3 \omega^2 [L_h h/b + (L_a - (1/2 + a) L_h) \alpha] e^{i(\omega t + \phi_L)} = 2qb\sqrt{R_L^2 + I_L^2} e^{i(\omega t + \phi_L)}$$
 (2.10)

After canceling $e^{i(\omega t + \phi L)}$:

$$\pi \rho b^{3} \omega^{2} \left[L_{h}(h/b) + (L_{\alpha} - (\sqrt{2} + a) L_{h}) \alpha \right] = 2qb \sqrt{R_{L}^{2} + I_{L}^{2}}$$

$$C_{L} \approx \sqrt{R_{L}^{2} + I_{L}^{2}}$$
(2.11)

For pitch case, h/b = 0, 2.11 reduces to:

$$\pi \rho b^3 \omega^2 [(L_{\alpha} - (\frac{1}{2} + a) L_h) \alpha] = 2qbC_{\alpha}$$
 (2.12)

Substitute $K_t = b\omega/U$ for ω^2 and $q = \frac{1}{2}\rho U^2$ into equation 2.12 which gives:

$$2\pi qbK_c^2(L_a - (\frac{1}{2} + a)L_b)\alpha = 2qbC_{La}$$
 (2.13)

After cancelling and substituting K_D for K_t :

$$\frac{\pi K_p^2}{4} \left[L_{\alpha} - (1/2 + a) L_h \right] \alpha = C_{L\alpha}$$
 (2.14)

This relationship can be further broken down into the real and imaginary parts:

Imag:
$$\frac{\pi K_p^2}{\Delta} \left[iL_{\alpha} - (1/2 + a) iL_h \right] \alpha = C_{L\alpha} \sin(\phi_L) \qquad (2.15)$$

Plunge Case: $\alpha=0$ using equation 2.11 gives:

Real:
$$\frac{\pi K_p^2}{4} [L_a - (\frac{1}{2} + a) L_h] \alpha = C_{La} \cos(\phi_L)$$
 (2.16)

$$\pi \rho b^3 \omega^2 L_h \frac{h}{b} = 2qbC_{Lh} \tag{2.17}$$

The panel code uses h/2b for analysis because it uses full chord vice half chord. Therefore equation 2.17 becomes:

$$2\pi\rho b^3 \omega^2 L_h(\frac{h}{2b}) = 2qbC_{Lh}$$
 (2.18)

Substituting as before for ω :

$$2\pi qbK_t^2L_h^2(\frac{h}{2b}) = 2qbC_{Lh}$$
 (2.19)

Cancel and substitute K_p :

$$(\frac{\pi K_p^2}{2}) (\frac{h}{2b}) L_h = C_{Lh}$$
 (2.20)

This can also be broken up into imaginary and real parts as before.

MOMENT:

Equating equations 2.7 and 2.9 results in:

$$\pi \rho b^{4} \omega^{2} \left(\left[M_{h}^{-} \left(\frac{1}{2} + a \right) L_{h} \right] \frac{h}{b} + \left[M_{\alpha}^{-} \left(\frac{1}{2} + a \right) \left(L_{\alpha} + M_{h} \right) + \left(\frac{1}{2} + a \right)^{2} L_{h} \right] \alpha \right)$$

$$= 4 q b^{2} \sqrt{R_{m}^{2} + L_{m}^{2}}$$
(2.21)

For pitch: h/b = 0

$$M_{\rm p} = 4 q b^2 \sqrt{R_m^2 + I_m^2} e^{i(\omega t + \phi_m)}$$
 (2.22)

$$C_{Max} = \sqrt{R_m^2 + I_m^2} \tag{2.23}$$

resulting in:

$$\pi \rho b^4 \omega^2 ([M_a - (1/2 + a) (L_a + M_h) + (1/2 + a)^2 L_h] \alpha) = 4qb^2 C_{M\alpha}$$
 (2.24)

After substituting and cancelling:

$$\frac{\alpha \pi K_p^2}{8} \left[M_\alpha - (\sqrt{2} + a) \left(L_\alpha + M_h \right) + (\sqrt{2} + a)^2 L_h \right] = C_{M\alpha}$$
 (2.25)

REAL $M_h = \frac{1}{2}$

$$\frac{\alpha \pi K_p^2}{8} \left[M_{\alpha} - (\frac{1}{2} + a) \left(L_{\alpha} + \frac{1}{2} \right) + (\frac{1}{2} + a)^2 L_h \right] = C_{M\alpha} \cos \left(\phi_{M\alpha} \right)$$
 (2.26)

IMAG: $M_h = 0$

$$\frac{\alpha\pi K_p^2}{8} \left[iM_{\alpha} - (\frac{1}{2} + a) (iL_{\alpha}) + (\frac{1}{2} + a)^2 iL_h \right] = C_{M\alpha} \sin(\phi_{M\alpha}) \quad (2.27)$$

For plunge, $\alpha \approx 0$, equation 21 reduces to :

REAL: $M_h = \frac{1}{2}$

$$\frac{\pi}{4}K_p^2(\frac{h}{2b})[M_h-(1/2+a)L_h]=C_{Mh}\cos(\phi_{Mh})$$
 (2.28)

IMAG: $M_h = 0$

$$\frac{\pi}{4} K_p^2 \left(\frac{h}{2b} \right) (1/2 + a) L_h = C_{Mh} \sin(\phi_{Mh})$$
 (2.29)

Comparisons are shown for various cases of pitch and plunge. The tables include pitch values of 1 (Tables 2.2-2.3) and 6.7 degrees (Tables 2.4-2.5), plunge (h/2b) values of .01 (Table 2.8) and .0833 (Table 2.6-2.7). The graphs include 1 degree pitch (Figures 2.7-12, 2.13-20), 6.7 degree pitch (Figures 2.21-28,2.29-36), .01 h/2b plunge (Figures 2.53-56), and .0833 h/2b plunge (Figures 2.37-44, 2.45-52).

4. Results

The tables and graphs show that the panel code predicts the Theodorsen results accurately. An initial question that was first addressed for the comparisons was how many cycles to use for good consistent phase results. Initial runs were made at several different cycle values and the results are shown in Table 2.1. It can be seen that the panel code predicts Theodorsen's results, using a cycle number of three. Increasing the cycle number just takes more computer time and only results in marginal increases in accuracy.

The most glaring difference appears in the I_M c_{Mh} comparisons of Figures 2.47-48. The panel code drops off sharply at the higher end of the reduced frequency spectrum. The reason for this is believed to be due to the magnitude of h/2b chosen for the comparison. The code was rerun for a

	Compari	son of Phase	Calculations U	sing Variou	s Cycles.	
		(Pitch, 6.7 deg., NA	CA 0007, .37c, 50 pa	enels top and bot	tom)	
Кр	# Cycles	CI Phase Angle	Cm Phase Angle	CI Amplitude	Cm emplitud	ie
1.00	1	182.0537	-54.409	0.4884	0.08937	
1.00	2	208.1592	-46.424	0.5109224	0.083932	
1.00	3	206.001	-44.313	0.51527	0.083169	
% Diff. 2/3		1.05%	4.76%	0.84%	0.92%	
1.00	4	204.9365	-43.33887	0.51668	0.082951	
1.00	5	204.3955	-42.86817	0.5172907	0.082865	
1.00	6	204.0596	-42.58497	0.517598	0.082822	
1.00	7	203.8291	-42.3916	0.517776	0.082792	
1.00	8	203.6031	-42.25684	0.51789	0.082784	
% Diff. 7/8		0.11%	0.32%	0.02%	0.01%	
3.60	2	264.44052	-59.79002	1.0931	0.212011	
3.60	3	261.9737	-58.29977	1.09954	0.21936	
% Diff. 2/3		0.94%	2.56%	0.59%	3.35%	
3.60	4	260.17877	-57.4404	1.10271	0.21903	
3.60	5	259.2686	-56.79395	1.104505	0.218845	
3.60	6	258.5186	-56.3252	1.105599	0.218739	
3.60	7	257.9483	-56.0098	1.106306	0.218673	
3.60	8	257.6163	-55.380567	1.106764	0.218632	
% Diff. 7/8		0.13%	1.14%	0.04%	0.02%	

TABLE 2.1 PHASE CALCULATION VS CYCLE NUMBER

series of h/2b values and the percent difference for the panel code to Theodorsen was plotted in Figure 2.4. This chart shows that the h/2b value chosen has a tremendous impact on the code results. An h/2b value of .01 gave an acceptable error of 10% at $K_p = 8$. Runs were completed with a value of .01 h/2b and the favorable results are shown in Figures 2.53-56.

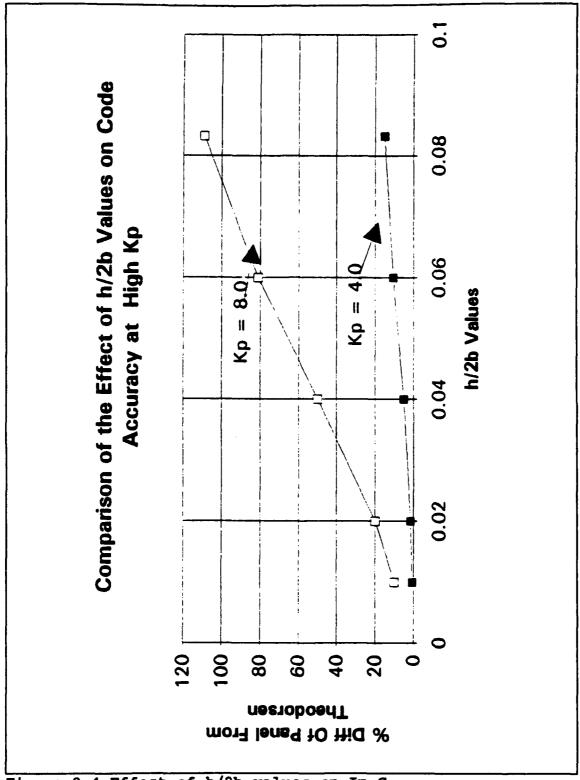


Figure 2.4 Effect of h/2b values on Im C_m

The colored				Companeon	of Penel C	Values with	mpanson of Panel Cl Values with Theordonan Results	eults.						
anel (equal to 2 x Theordorean Kt)			-	(pitch, 1.0 de	19., .37c, h	IACA 0007.	50 penels top 4	and bottom.	3cyc66calc.)					
10.096452 4,74% 0.01062 0.00786418 37.24% 0.1030861 0.0867874 4.86% 174.01008 175.42145 0.0085343 4.40% 0.01064 0.00786418 37.24% 0.10013838 0.0865346 4.71% 173.72806 175.5214 0.008534 4.11% 0.01064 0.0074695 4.65% 0.0096992 0.0867706 4.46% 173.72806 175.5214 0.008534 4.11% 0.01064 0.0074695 4.65% 0.0086349 0.0087706 4.46% 173.72806 175.2214 0.008534 4.11% 0.000649 0.00016269 0.00016269 0.008510 0.086239 0.0862706 4.46% 173.72806 176.5214 0.008023 3.46% 0.000648 0.00016269 0.00016269 0.008531 0.086231 0.0862705 3.46% 0.000648 0.00016269 0.00016269 0.00852214 0.008029 0.36% 177.78696 181.0773 0.006239 0.0006780 0.0006720 0.008230 0.0086230 0.0086284 0.000648 0.0006720 0.008230 0.008230 0.008230 0.0086284 0.0006720 0.0006720 0.008231 0.086281 0.0772826 0.37% 181.8966 181.02716 0.0077280 0.0077280 0.0077280 0.32% 181.8962 180.89762 0.0077281 1.34% 0.00328 0.0006720 0.00767280 0.00772809 0.0077280				Kpanel (eque	I to 2 x Th	lordonsen Kti			%DIFF taken v	vrt Theordon	on values.	-		
1,000,000,000,000,000,000,000,000,000,0														
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0.086462 4.74% 0.01062 0.00786418 37.24% 0.1036801 0.066346 4.86% 174.01008 175.4245 0.086343 4.40% 0.01064 0.00746657 46.52% 0.1006388 0.0666346 4.71% 173.72806 175.5214 0.0802634 4.11% 0.01064 0.0007646 0.0007663 0.0007669 4.71% 173.72806 175.5214 0.080278 0.000669 0.00162697 0.0666023 0.066702 3.66% 1.71% 177.73856 186.7321 0.082367 3.46% 0.000328 0.0007664 0.0862831 0.0861026 3.56% 177.73856 187.73856 187.73857 0.077664 3.46% 0.000328 0.0006731 70.86% 0.0862831 0.07824026 3.57% 177.73866 187.23 186.67% 0.0862831 0.07824026 3.37% 181.88.5286 186.67% 0.07824026 3.56% 177.73866 186.67% 0.07824026 3.27% 181.88.5286 188.8826 188.8828 188.8828 188.8828														
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0.062534 4.11% 0.0104 0.0064761 60.65% 0.0668972 0.0827606 4.46% 173.83872 176.9857 0.060022 3.81% 0.00644 0.00610846 64.80% 0.08401613 0.086022 3.86% 174.23726 176.7541 0.060022 3.46% 0.000480 0.00162887 30.086782 3.86% 177.1373 178.81387 0.0276640 3.46% 0.000480 0.000419 236.80% 0.0861082 3.60% 177.719586 181.6773 0.0776641 3.46% 0.000470 0.000470 0.000470 0.000470 177.719586 181.6273 178.8182 0.0776640 3.46% 0.000470 0.000470 0.000470 17.000470 181.888268 181.88876 181.288 181.68876 181.288 181.68876 181.88876 181.88876 181.88876 181.88876 181.88876 181.88876 181.88876 181.88876 181.88876 181.88876 181.88876 181.888776 181.888776 181.888776 181.88876 181.88876 <t< th=""><th>12.5</th><th></th><th></th><th>Q</th><th>4.40%</th><th>0.01094</th><th>0.00746667</th><th>46.62%</th><th></th><th>0.0956346</th><th></th><th></th><th>1 1</th><th>1.02%</th></t<>	12.5			Q	4.40%	0.01094	0.00746667	46.62%		0.0956346			1 1	1.02%
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0.062367 3.46% 0.00328 -0.0024119 236.98% 0.0062831 0.002402 3.50% 177.79566 181.9773 0.079646 3.46% -0.00048 -0.0067203 92.86% 0.0823214 0.0762696 3.12% 180.33406 184.8266 0.077263 4.06% -0.00376 0.003744 12.33% 0.0772862 3.27% 181.9686 187.02716 0.077271 1.34% -0.01176 -0.013414 12.33% 0.0772862 2.56% 188.62862 189.8266 187.627 0.077271 1.34% -0.01178149 8.80% 0.07738067 0.0773868 1.35% 188.5762 188.6773 0.077271 1.34% -0.02328 -0.03606 -0.03606 -0.0763387 0.0773866 1.35% 188.7552 188.8752 188.8752 188.8756 188.8756 188.8756 188.8756 188.8756 188.8756 188.8756 188.8756 188.8756 188.8756 188.8756 188.8756 188.8756 188.8756 188.8756 188.8756 188	8.26			9	3.58%	0.00668		309.38%			3.86%	175.71373	178.91357	1.79%
0.079646 3.49% -0.00048 -0.0067203 92.86% 0.0823214 0.0798296 3.12% 180.33406 184.8206 0.077663 4.09% -0.00278 -0.003414 12.33% 0.07928065 3.37% 181.96856 187.02716 0.077215 3.01% -0.01176 -0.013414 12.33% 0.07728067 0.0772862 2.59% 188.62692 189.0278 0.077701 1.34% -0.01632 -0.0178149 8.80% 0.07738067 0.076348 182.17543 193.57073 0.077701 1.34% -0.02328 -0.0246749 5.65% 0.0763368 0.07738067 0.07738068 1.36% 182.17543 193.57073 0.06233 0.26% -0.036066 -0.036006 3.20% 0.07673387 0.077102 0.48% 206.86223 207.8126 216.8687 0.06234 0.0467313 2.34% 0.07808666 0.07808666 0.07808666 0.04808 214.8683 214.86623 214.86623 214.86623 214.86623 214.86623 214.86623	S		_	Ģ	3.46%	0.00328	-0.0024119		0.0862831	0.0824026	3.60%		181.6773	2.14%
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0.074217 1.92% -0.01932 -0.0178149 8.90% 0.0738696 1.36% 192.17643 193.67073 0.077761 1.34% -0.02328 -0.0246746 6.66% 0.0763649 0.0768649 0.025% 197.75153 198.67023 0.066233 0.26% -0.03469 -0.036806 3.20% 0.0767332 0.077102 0.48% 206.86223 207.67124 0.066233 0.87% -0.04664 -0.0467313 2.34% 0.0760668 0.0677102 0.48% 206.86223 207.67124 0.066408 3.86% -0.0467313 2.34% 0.0760668 0.067743 1.43% 216.24126 216.61686 0.066408 3.86% -0.0467313 2.34% 0.0760668 0.0603233 2.83% 228.41286 216.61686 0.066408 3.86% -0.10672 -0.10672 -0.10672 2.14% 0.08767246 0.06033% 2.83% 228.41286 216.88287 1.62684 3.86% -0.106772 -0.10672 -0.10672 -0.10672	3.33			Ŷ	3.01%	-0.01178	-0.013414	12.33%	0.07929687	0.0772982		188.62862		0.77%
0.068284 0.026% -0.02328 -0.0246746 6.66% 0.0768646 0.0768646 0.026% 1.34% -0.03466 -0.0346746 5.66% 0.07673367 0.077102 0.04% 200.8523 207.67124 0.066233 0.026% -0.034664 -0.036806 3.20% 0.07673367 0.077102 0.44% 206.86223 207.67124 0.066408 3.04673 2.34% 0.0780666 0.0602443 1.43% 216.24126 215.61696 0.066408 3.04673 2.34% 0.0780666 0.0603233 2.83% 228.4126 215.61696 0.066408 3.04673 1.010087 3.63% 0.1404618 0.1186806 4.63% 248.4632 246.8287 0.06661 71.72% -0.10072 -0.1100887 3.63% 0.1772564 0.44% 244 244 244 244 244 244 244 244 244 244 244 244 244 244 244 244 244 245 267.31661 267.31662	2.94			o.	1.92%	-0.01632	-0.0179149	8.90%		0.0763489	1.35%			0.72%
0.066234 0.26% -0.03466 -0.036806 3.20% 0.07073367 0.077102 0.46% 206.6623 207.67124 0.066233 0.87% -0.0467313 2.34% 0.0760868 0.0802443 1.43% 216.24126 216.61696 0.066406 3.89% -0.046731 2.34% 0.0760868 0.0803233 2.83% 226.41288 228.8726 0.066406 0.066036 -0.0680368 2.14% 0.08767245 0.0803233 2.83% 226.41288 228.8726 0.06671 -0.100072 -0.1100687 3.63% 0.11404618 0.1186806 4.63% 246.4632 246.89297 0.008661 71.72% -0.178738 -0.1888368 4.82% 0.17876643 0.1860431 4.61% 208.2678 246.89297 1.82884 -0.368727 -0.3806373 6.73% 0.381478 0.4138662 6.44% 283.4206 283.1478 1.62884 -0.10618 -0.100687 4.44% 0.11310788 0.186043 6.25% 283.368 283.1478	2.6			0	1.34%	-0.02328	-0.0248748	5.06%	0.07835548	0.0758848				0.61%
0.066233 0.87% -0.04673131 2.34% 0.07606686 0.06024431 1.43% 215.24126 215.61696 0.06640e 3.86% -0.0680368 2.14% 0.08767245 0.0003233 2.93% 228.41288 228.8725 0.046737 10.36% -0.1006072 -0.1100687 3.63% 0.11404619 0.1195806 4.63% 248.44632 246.86287 0.008661 71.72% -0.178739 -0.1886358 4.82% 0.17875643 0.189634 4.61% 226.43% 226.222 267.31661 1.02684 3.86% -0.178739 -0.1886358 4.82% 0.17875643 0.189642 6.73% 246.4632 246.86227 267.31661 1.02684 -0.186727 -0.3806373 6.73% 0.04677 6.44% 288.264 6.74% 289.267 289.28698 1.02685 5.86% -0.106887 4.44% 0.11310788 0.18644 248.42059 248.2059 248.92067 1.02686 1.0.28 -0.10618 0.18836 0.1772286	2	-	-0.06846	Q.	0.28%	-0.03466	-0.036806	3.20%	0.07673387	1 1				0.39%
0.06640e 3.99% -0.06608 -0.06803681 2.14%1 0.08767245 0.0803233 2.93%1 228.41289 228.8725 0.046737 10.36% -0.106072 -0.11006871 3.63%1 0.1195606 4.63% 248.44832 246.89287 0.008661 71.72% -0.179738 -0.18863581 4.82%1 0.17976643 0.1890431 4.91% 269.2022 267.31651 1.926894 3.86% -0.166727 -0.38063731 6.73%1 0.38134264 0.4138652 6.44% 293.65769 293.14781 blove were calculated using 200 panels top and bottom and 4 cycles of 100 calculations. 6.44% 293.65769 293.14781 0.046737 10.89% -0.10618 -0.1100687 4.44%1 0.11310788 0.1196906 6.41% 248.42069 246.89287 0.046737 10.89% -0.10618 -0.10688368 6.18%1 0.17722998 0.119660431 6.25% 291.00630 293.14781 1.62684 16.28% -0.35464 -0.3806373 6.87860 0.1896468 0.4138662	1.67			0-	0.87%	-0.04564	-0.0467313		0.07909695	0.0802443	1.43%	215.24128		0.17%
0.046737 10.36% -0.106072 -0.1100687 3.63% 0.11404619 0.1196806 4.63% 248.44832 246.99287 0.008661 71.72% -0.179739 -0.18863681 4.82% 0.17976643 0.1890431 4.91% 269.2022 267.31661 1.926894 3.86% -0.366727 -0.38063731 5.73% 0.38134264 0.4138652 5.44% 293.65769 283.14781 blove were calculated using 200 panels top and bottom and 4 cycles of 100 calculations. 6.44% 293.65769 293.14781 0.046737 10.89% -0.10618 -0.1100687 4.44% 0.11310788 0.1196806 5.41% 248.42069 246.89287 0.048737 10.89% -0.10618 -0.10618 0.1100687 4.44% 0.11310788 0.1186063 5.41% 226.42069 246.89287 1.026864 16.28% -0.35464 -0.3806373 6.81% 0.37869468 0.4138662 8.21% 291.00030 293.14781	1.26			o.	3.88%	-0.00068	-0.0680368	2.14%	0.08767245	0.0003233		229.41288		0.24%
0.008661 71.72% 0.179739 0.18883681 4.82%i 0.179766431 0.1896232 267.31651 1.926894 3.86% -0.366727 -0.38063731 5.73%i 0.391342641 0.4138652 5.44%i 293.65769 293.14781 blove were calculated using 200 panels top and bottom and 4 cycles of 100 calculations. 6.44%i 293.65769 293.14781 0.046737 10.89%i -0.10618 -0.1100687i 4.44%i 0.11310788 0.1195806 5.41%i 248.42069 246.892871 0.008951 43.73%i -0.17716 -0.1898368 6.18%i 0.17722988 0.4138652 8.21%i 291.00030 293.14781 162684 16.28%i -0.35464 -0.3606373 6.81%i 0.37869468 0.4138652 8.21%i 291.00030 293.14781	0.83			Q	10.36%	-0.106072	-0.1100687	3.63%	0.11404619	0.1195805	4.63%	248.44832		0.59%
1626984 3.86% -0.368727 -0.3906373	0.5	4	-0.002503	Ģ	71.72%	-0.179738	0.1886358	4.82%	0.17975643	0.1890431	4.91%	200.2022	_	0.71%
herve were calculated using 200 panels top and bottom and 4 cycles of 100 calculations. 3.046737 10.89% -0.10618 -0.1100687 4.44% 0.11310788 0.1195806 5.41% 248.42059 246.89297 3.008651 43.73% -0.17716 -0.1888358 6.18% 0.17722998 0.1890431 6.25% 268.38983 267.31651 3.008654 18.28% -0.35464 -0.3806373 6.81% 0.37989468 0.4138652 8.21% 291.00639 293.14781	0.25		0.1564088	0.	3.86%	-0.358727			0.39134264	0.4138662		293.55769	_	0.14%
2.4 -0.0416 -0.0466 -0.0466 -0.10589 -0.10589 0.1196806 5.41% 248.42069 246.89297 4 -0.00488 -0.046737 10.89 % -0.17716 -0.1888368 8.18% 0.17722998 0.1860431 9.26% 288.38983 267.31651 8 0.1362 0.1626884 16.28% -0.35464 -0.3806373 8.81% 0.3788468 0.4138562 8.21% 291.00936 293.14781	Values	for Kp equal	to 2.4,4, and		o calculated	1 uning 200 p	eneis top and	bottom and	4 cycles of 10	O calculation				
2.4 -0.046737 10.89% -0.10518 -0.1100687 4.44% 0.11310789 0.1196806 5.41% 248.42069 246.89287 4 -0.00488 -0.006861 43.73% -0.17716 -0.1868368 0.18710 0.18722988 0.1890431 6.25% 268.38963 267.31651 8 0.1362 0.1626884 16.28% -0.3806373 6.81% 0.3786468 0.4138652 8.21% 291.00036 293.14781	at set		were calculate	nd Jeing 75 pa	nee and 34	ycescale.								
4 -0.00488 -0.008851 43.73% -0.17716 -0.18883581 6.18% 0.17722988 0.1880431 6.25% 268.38883 267.31651 8 0.1362 0.1362 0.1626884 16.28% -0.35464 -0.3806373 6.81% 0.3788468 0.4138652 8.21% 291.00636 293.14781	0.83			Ŷ	10.99%	-0.10518		4.44%	0.11310788	0.1195805	5.41%	248.42069		0.58%
8 0.1342 0.1626864 16.28% -0.35464 -0.3806373: 6.81% 0.37986498 0.4136552 8.21% 291.00636 293.14781	0.6			Ģ	43.73%	-0.17716		6.18%	0.17722998	0.1890431	0.25%	268.38983	267.316611	0.40%
	0.25			0	16.28%	-0.35464	-0.3806373	6.91%	0.37989468	0.4138662			293.14781	0.73%

TABLE 2.2 1 DEGREE PITCH CL

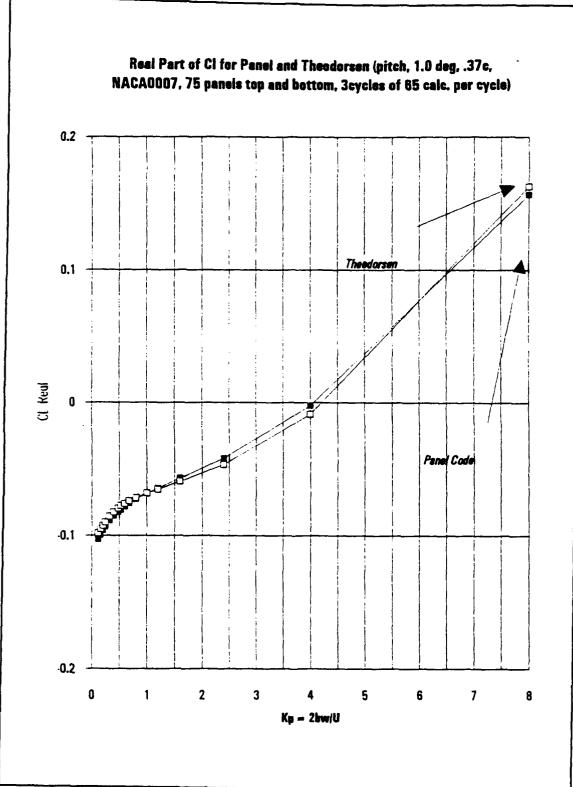


Figure 2.5 1 Degree pitch C_L Re

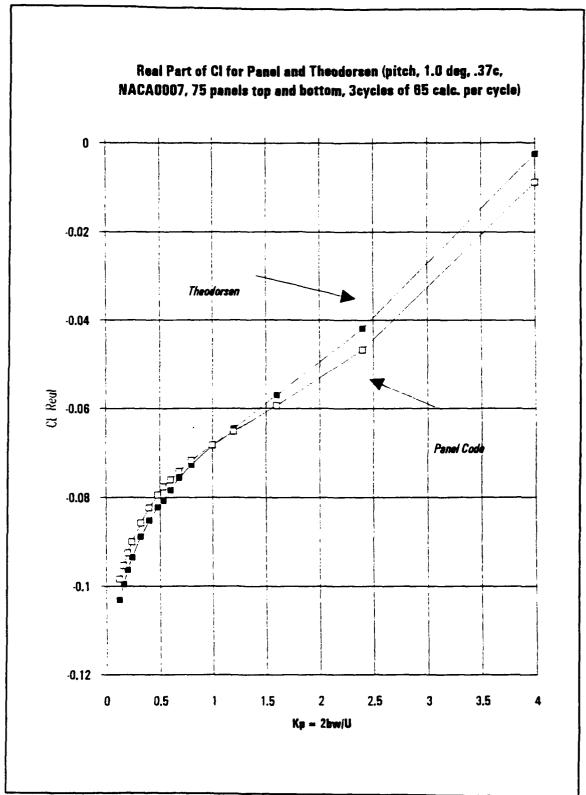


Figure 2.6 1 degree pitch C_L Re

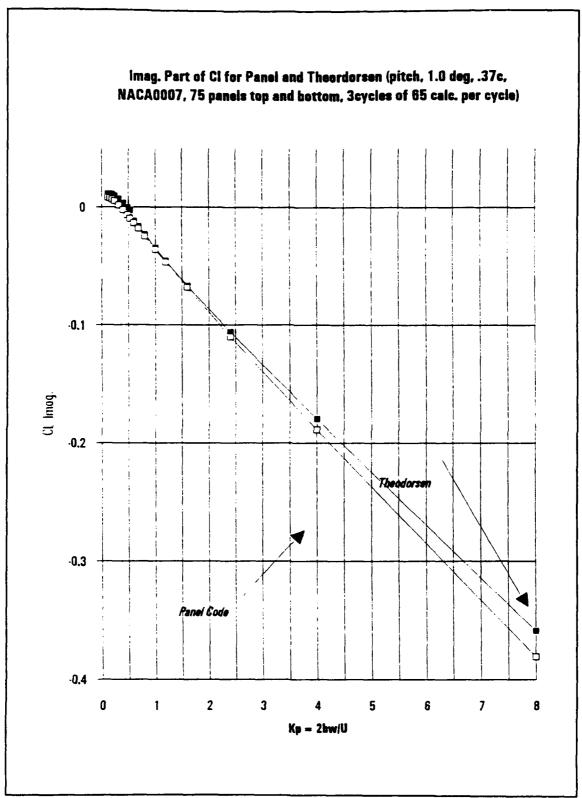


Figure 2.7 1 Degree pitch C_L Im

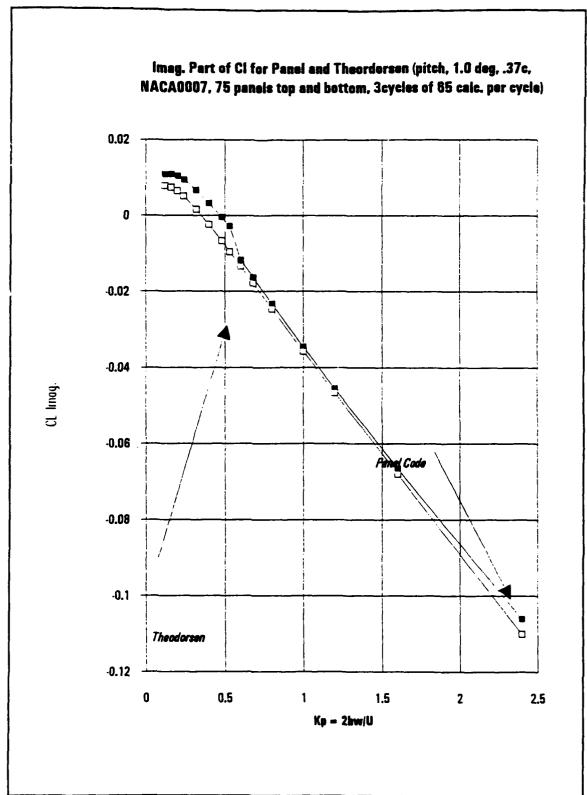


Figure 2.8 1 Degree pitch C_L Im

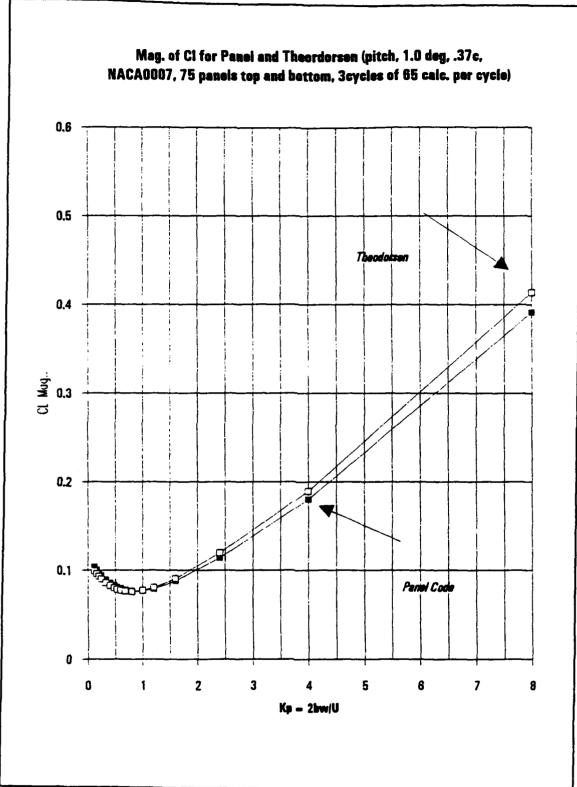


Figure 2.9 1 Degree pitch C_L Magnitude

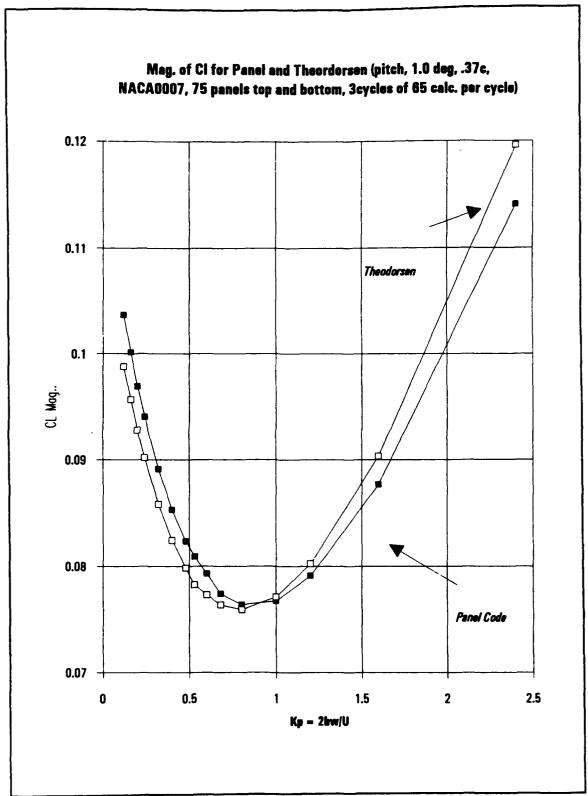


Figure 2.10 1 Degree pitch C_L Magnitude

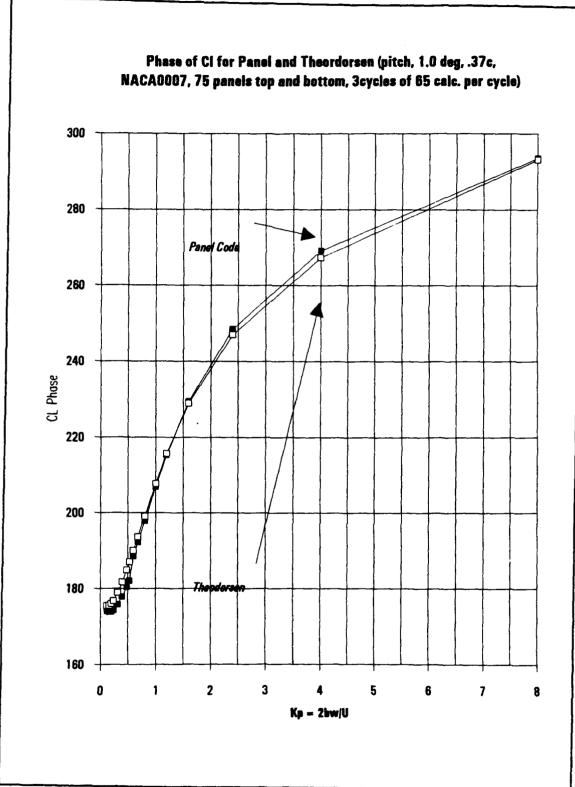


Figure 2.11 1 Degree pitch C_L Phase

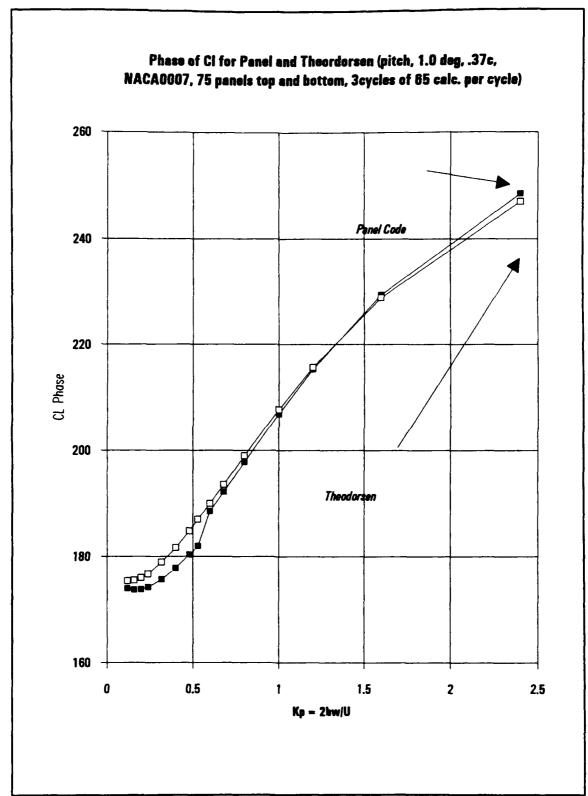


Figure 2.12 1 degree pitch C_L Phase

State	
% DIFF Mag Pan. Mag Tha. % DIFF Phase Ph. Phase Th. % DIFF 1.14% 0.0121665 0.0121192 0.36% 347.66314 347.66746 0.36% 0.0118615 0.0118626 0.010% 344.67699 346.6469 0.054% 0.0116463 0.0117148 0.05% 340.3866 340.3868 1.34% 0.0112281 0.0115284 2.60% 336.64009 335.283183 3.34% 0.0112281 0.0116526 2.014483 3.14% 330.14016 328.83183 4.04% 0.0111272 0.0114663 3.14% 330.14016 328.283183 4.04% 0.0111272 0.0114663 3.14% 330.14016 328.283183 4.04% 0.0111272 0.0114663 3.14% 330.14016 328.83183 4.04% 0.011270 0.0116670 3.47% 328.37699 328.68817 6.06% 0.0112694 0.0126992 3.15602 328.6892 313.6409 6.26% 0.0112694 0.0126992	Comparison of Panel Moment Aerodynamic Values (CM.) with interest of the control
% DIFF Mag Pan. Mag The. % DIFF Phase Pn. Phase Pn. Phase Th. % DIFF 1,14% 0.0121065 0.0121182 0.38% 347.66314 347.66745 0,26% 0.0116956 0.0119936 0.010% 344.67589 344.6769 0,64% 0.0116483 0.0117148 0.67% 342.61383 342.6187 1,34% 0.0112281 0.0115289 0.0115289 3.40.3066 340.32136 1,34% 0.0112281 0.0115289 0.011434 2.61% 333.18163 332.83184 4,04% 0.011279 0.0114663 3.14% 330.14016 326.83183 4,04% 0.011279 0.0114663 3.14% 330.14016 326.83183 4,04% 0.011279 0.0114663 3.14% 330.14016 326.88186 6.26% 0.0116644 0.0126661 6.17% 326.86070 326.88433 4.81% 0.0116644 0.0126662 7.27% 320.86814 300.120643 6.26% 0.012664	Kpenel (equal to 2 × Theordonean Kt)
1.14% 0.0121065 0.0121102 0.38% 347.66314 347.66745 0.36% 0.0110015 0.0110026 0.10% 344.67599 344.0459 0.056% 0.0156% 0.0117148 0.67% 342.61393 342.6187 1.34% 0.0114751 0.0115200 0.057% 342.61393 342.6135 3.34% 0.0112201 0.0115200 0.0114134 2.61% 339.19163 332.93194 4.04% 0.0111272 0.0114003 3.14% 330.14016 329.83193 3.90 0.0111272 0.0114003 3.14% 330.14016 329.83193 3.90 0.011607 0.0116070 0.0116070 3.14% 330.14016 329.83193 3.90 0.011607 0.0116070 0.	Rt % DIFF Imag
0.35% 0.0118816 0.0118838 0.10% 344.87696 344.9459 0.64% 0.0116483 0.0117148 0.67% 342.61383 342.6187 1.34% 0.0112281 0.0115284 0.69% 340.39666 340.32136 7.23% 0.0112281 0.0115284 2.60% 336.64008 336.28363 3.34% 0.0111272 0.0114883 3.14% 330.14016 329.83184 4.04% 0.01111867 0.0116576 3.47% 328.37698 328.23804 4.81% 0.0112888 0.0117836 4.45% 328.0702 326.88186 6.18% 0.011864 0.0128881 6.17% 323.68022 323.68433 6.08% 0.012884 0.0128881 6.17% 323.68177 316.86403 6.08% 0.012884 0.0128882 7.27% 316.88177 316.86403 6.20% 0.0137407 0.0148688 8.13% 312.86886 313.6408 6.34% 0.0232887 0.0262226 7.63% 306.13184 306.28271 6.14% 0.0223884 0.0262226 7.63% 306.2803 312.05682 3.04% 0.0223884 0.0252226 11.22% 303.83134 308.28271 6.14% 0.0223884 0.0252226 11.22% 303.83134 308.28271 6.34% 0.0047816 0.1123447 15.62% 318.05617 325.27302	0,01188 0,0118391 0,36%
0.64% 0.0116483 0.0117148 0.67% 342.61383 342.6187 1.34% 0.0114761 0.0116286 0.86% 340.38686 340.32136 7.23% 0.0111281 0.01116284 2.60% 336.64008 335.283184 4.04% 0.0111272 0.0114134 2.61% 333.18163 332.83184 4.04% 0.0111272 0.0114863 3.14% 330.14016 328.83183 3.54% 0.0111667 0.0116576 3.47% 328.37688 328.23804 4.81% 0.0111867 0.0115676 3.47% 328.37688 328.23804 6.18% 0.0111864 0.0126881 6.17% 323.68022 323.68433 6.08% 0.013684 0.0126881 6.67% 320.0208 320.66177 6.18% 0.0136265 0.0180666 8.13% 312.6682 3.06% 0.1020471 0.1123447 8.17% 322.68932 326.27302 6.14% 0.0223887 0.0262226 7.63% 306.13184 308.28271 6.14% 0.0223834 0.0262226 11.22% 303.83134 308.28271 6.14% 0.0023834 0.0262226 11.22% 303.83134 308.28271 6.32% 0.0377606 0.04333 12.86% 308.20814 312.06682 2.84% 0.0047816 0.1123447 16.62% 318.06617 326.27302	0.0114866 0.14%
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7.23% 0.0112281 0.0116284 2.60% 336.84008 335.283184 3.34% 0.0111288 0.0114134 2.51% 333.18163 332.83184 4.04% 0.0111272 0.0114683 3.14% 330.14016 328.83893 3.64% 0.0111867 0.0115676 3.47% 328.37688 328.23804 4.81% 0.0111864 0.0126881 6.17% 323.88022 323.88433 6.08% 0.012884 0.0126881 6.67% 320.0203 6.08% 0.013884 0.0138882 7.27% 316.86177 316.86403 6.26% 0.012649 0.0138882 7.27% 316.86177 316.86403 6.26% 0.012649 0.0138882 7.27% 316.86177 316.86403 6.26% 0.012641 0.0126488 8.13% 300.13184 308.28271 6.14% 0.0223887 0.0262226 7.63% 300.08103 312.05682 3.06% 0.1020471 0.1123447 8.17% 322.56932 325.27302 6.14% 0.0223834 0.0252226 11.22% 303.83134 308.28271 6.32% 0.0047816 0.1123447 16.62% 318.06617 325.27302	18 0.93%
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-0.032172 6.32% 0.0377606 0.04333 12.88% 306.20814 312.06882 -0.063889 2.84% 0.0847816 0.1123447 15.62% 319.05617 325.27302	O R3. 2 A O O 12E O O 1EA9BB 20 O SK. J.
-0.063888 2.84% 0.0847818 0.1123447 15.62% 319.05517 325.27302	0.0290264 23.17%
	0.0023334 22.45%

TABLE 2.3 1 DEGREE PITCH CM COMPARISON

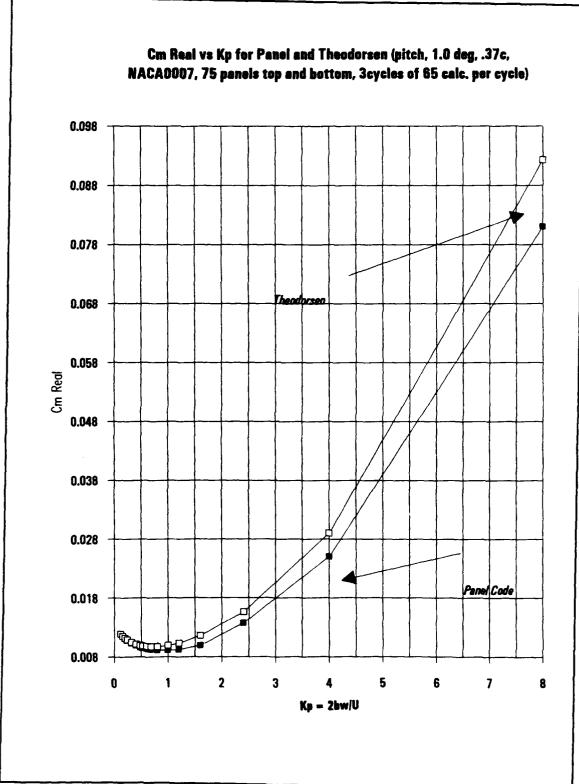


Figure 2.13 1 Degree pitch C_M Re

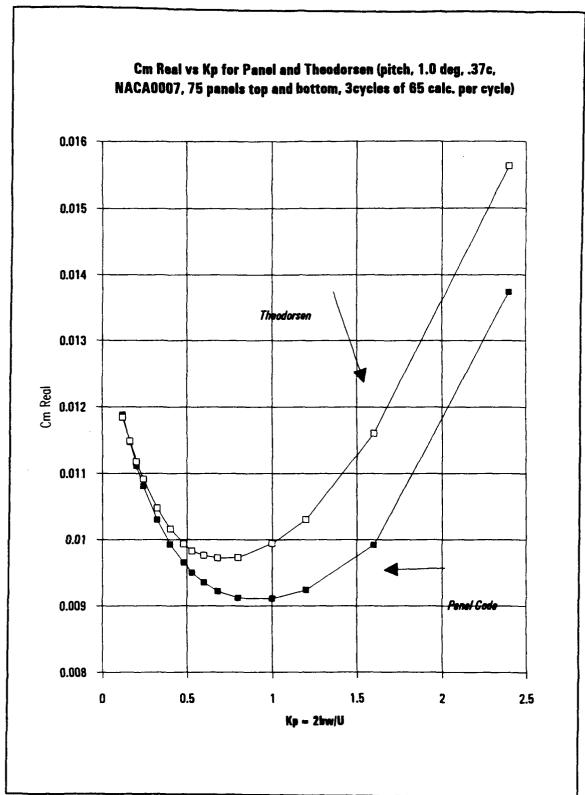
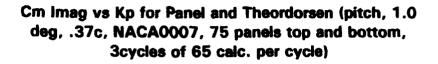


Figure 2.14 1 Degree pitch C_M Re





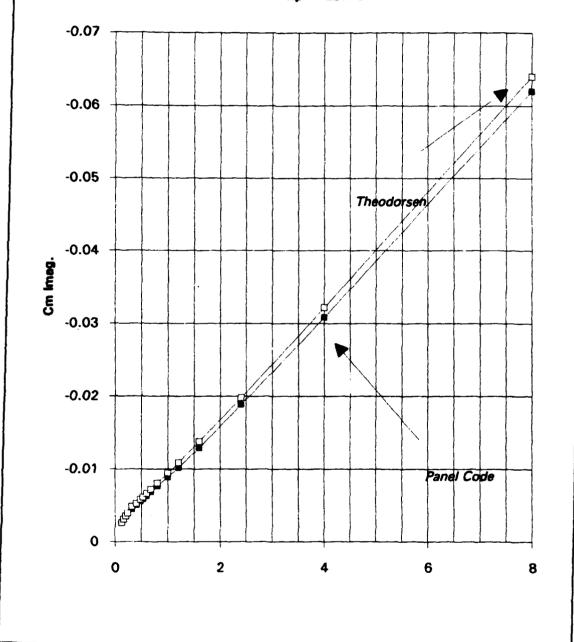
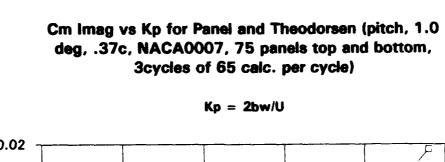


Figure 2.15 1 Degree pitch C_M Im



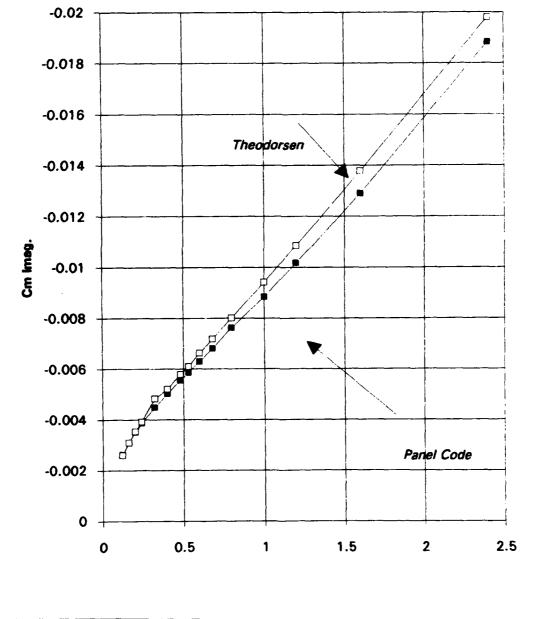


Figure 2.16 1 Degree pitch C_M Im

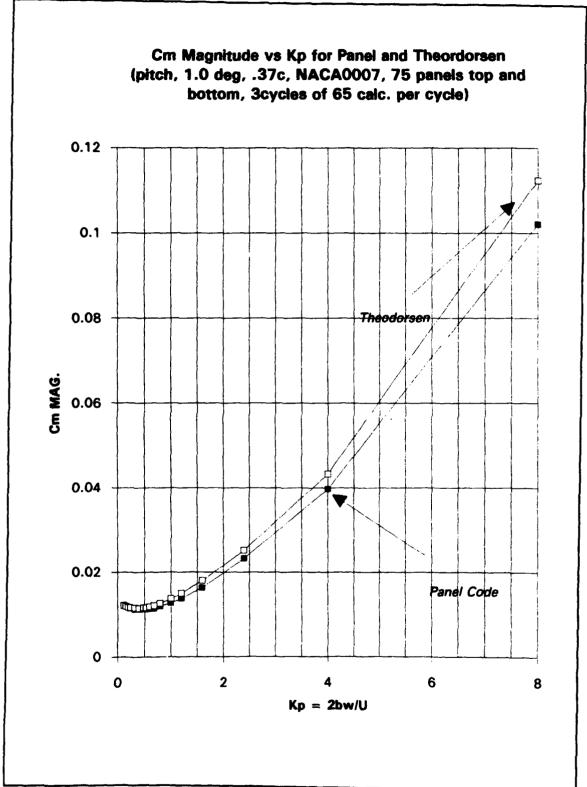


Figure 2.17 1 Degree pitch C_M Magnitude

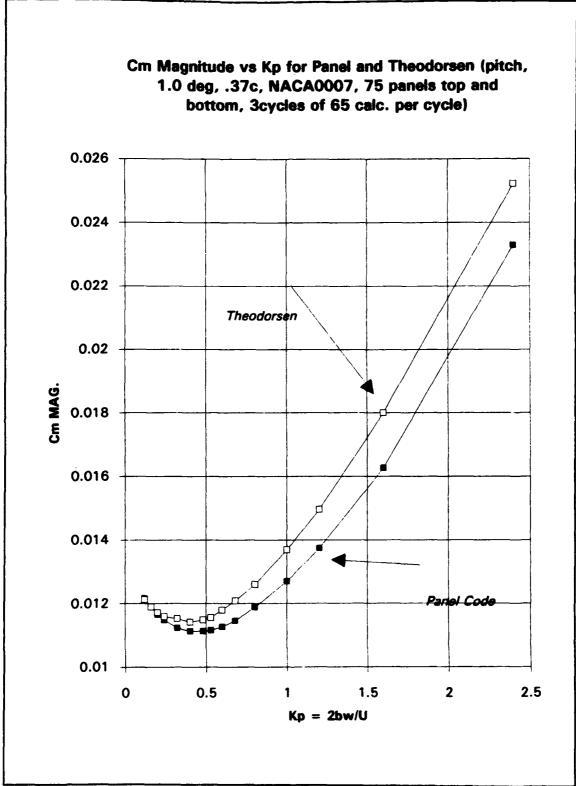


Figure 2.18 1 Degree pitch C_M Magnitude

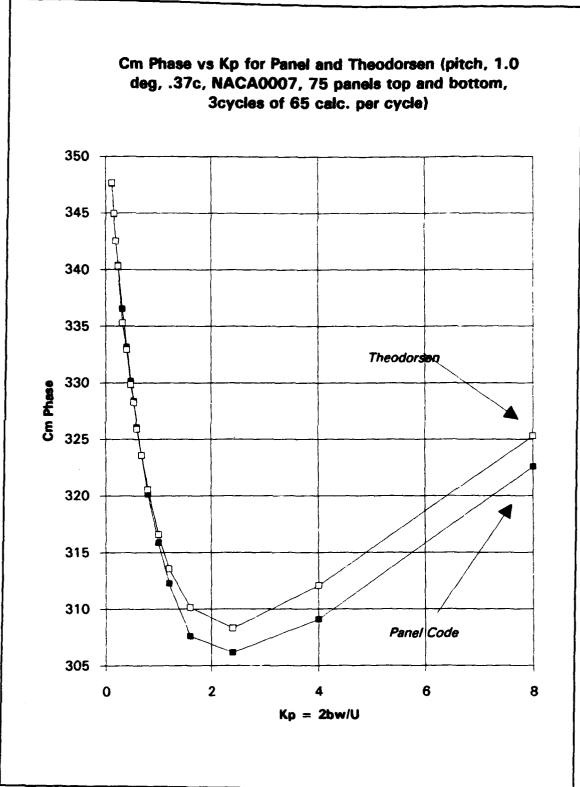


Figure 2.19 1 Degree pitch C_M Phase

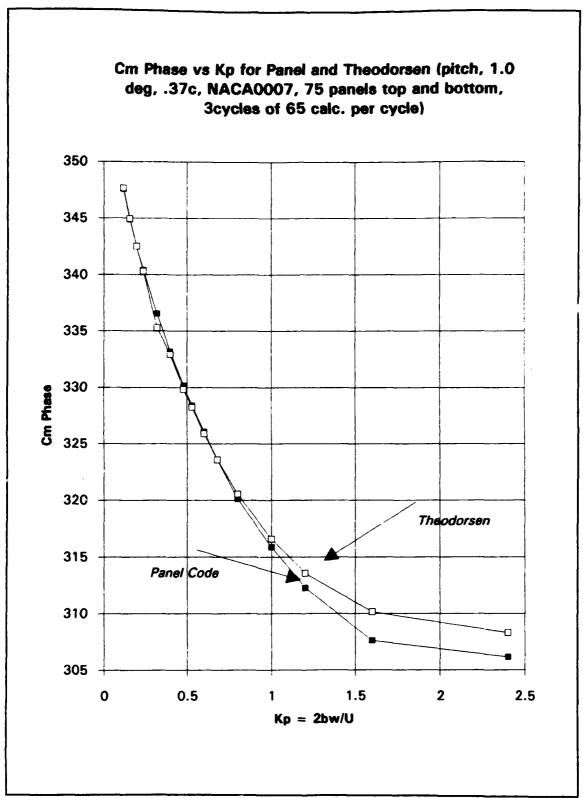


Figure 2.20 1 Degree pitch C_M Phase

(juit.), 6.7 deg., 37c, MACA D007, 75 peacht top and buttont, 3cyc@bcatc.] (juit.), 6.7 deg., 37c, MACA D007, 75 peacht top and buttont, 3cyc@bcatc.] (juit.), 6.7 deg., 37c, MACA D007, 75 peacht top and 7 late. % Diff. Mag Pen. Mag Tec. Mag	2	-	of Penel CL	Values with	Comparison of Penal CL Values with Theordorson Results	Resetts							
9.00FF taken wrt Theerterzan values. 1168 0.052824 35.51% 0.082748 1727 0.050026 44.46% 0.088337 1724 0.0434 61.84% 0.084589 1824 0.05023 41.84% 0.084589 1824 0.0542133 81.63% 0.652407 1828 0.01618 241.83% 0.652407 1828 0.06414 34.82% 0.6524808 1878 0.08874 24.46% 0.6524808 1879 0.12003 19.02% 0.615703 1806 0.16532 17.15% 0.651703 1816 0.45584 9.58% 0.586841 1742 0.03131 11.20% 0.6527437 1816 0.45584 9.58% 0.586841 1742 0.03131 11.20% 0.527437 1816 0.45584 9.58% 0.586841 1742 0.73748 8.55% 0.785035 1821 2.5489 11.06% 3.002211 1874 -1.2652 5.36% 1.215297 1874 -1.2652 5.36% 1.215297	2	Mich. 8.7 4	eg37c, NA	CA 0007. 7	penek tep a	ed bettem. 3c	yc65calc.)						
in. imag Theo. % Diff. Mag Pan. IA 7158 0.052824 35.51% 0.082748 7227 0.050026 44.46% 0.082748 7224 0.050028 44.46% 0.082608 6074 0.0108 294.86% 0.026609 3054 0.0108 24.86% 0.026600 4774 0.0108 24.86% 0.056600 4774 0.06414 34.82% 0.555480 6087 0.12003 18.02% 0.555480 6087 0.18532 17.15% 0.50779 2097 0.12003 18.02% 0.555480 2007 0.18532 17.15% 0.51037 7804 0.18532 17.15% 0.51037 7804 0.3131 11.20% 0.557437 7442 0.73746 8.55% 0.56641 5687 -1.2652 0.06% 1.257844 827 -2.5480 11.06% 3.002211 8048 -2.5480	X	tabe) jeued;	of to 2 x The	inderson Kt)	-	SOFF taken	art Theordo	rsen values.					
Inmed Theo. % DIFF. Mag Pen. IA 7158 0.052824 35.51% 0.082748 7227 0.050028 44.46% 0.08537 7224 0.0434 81.65% 0.085837 6214 0.0434 81.65% 0.08589 6214 0.0100 244.86% 0.68244 2262 0.01616 241.85% 0.58544 3584 0.06414 34.82% 0.58548 4174 0.06414 34.82% 0.58548 6072 0.12003 18.02% 0.515703 2067 0.12003 18.02% 0.515703 2067 0.12003 18.02% 0.515703 2067 0.10532 17.15% 0.51779 2067 0.2399 13.01% 0.511037 7442 0.0313 11.20% 0.51037 5687 -1.2652 0.066% 1.257644 8251 -2.5486 1.216287 8048 -2.5486 12.01%													
7158 0.052824 35.51% 0.882748 7024 0.0434 61.84% 0.882748 6214 0.05424 61.84% 0.84580 6214 0.05424 61.84% 0.84580 6214 0.0542133 81.85% 0.852409 6214 0.0100 294.89% 0.852409 6284 0.006414 34.82% 0.856540 6778 0.00672 0.12003 19.02% 0.524900 6972 0.12003 19.02% 0.524900 6972 0.12003 19.02% 0.524900 6972 0.12003 19.02% 0.524900 6972 0.12003 19.02% 0.524900 6972 0.12003 19.02% 0.524900 6972 0.12003 19.02% 0.596941 7442 0.73134 11.20% 0.527437 1216 0.45564 9.56% 0.269691 1.006% 1.257644 8521 0.26769 11.006% 1.257644 8521 0.26769 11.006% 1.257644 8521 0.26769 11.006% 1.257644 8521 0.26769 11.006% 1.257644 8521 0.26769 11.006% 1.257644 8521 0.26769 11.006% 1.257644 8521 0.26769 11.006% 1.257644 8521 0.26769 11.006% 1.257644 8521 0.26769 11.006% 1.257644 8521 0.26769 11.006% 1.25769 11.25769	1kt.			% DIFF.	Imag Pan.		% DIFF.		Mag Theo.	% OFF.	% DIFF. Phase Pn.	Phase Th.	% DIFF.
7158 0.052824 35.51% 0.892748 7227 0.05026 44.46% 0.89589 70224 0.0434 61.84% 0.89589 82214 0.0342133 81.63% 0.52569 8222 0.0108 284.86% 0.562407 8282 0.0108 241.83% 0.5652407 8282 0.01618 241.83% 0.525289 872 0.1203 19.02% 0.524806 972 0.1203 19.02% 0.524806 972 0.1203 19.02% 0.527437 7804 0.03131 11.20% 0.527437 7726 0.45564 8.56% 0.73748 8.56% 0.78564 8.25% 0.78564 8.25% 0.785635 8221 -2.5486 11.06% 1.257644 8221 -2.5486 11.06% 1.257644 8221 -2.5486 11.06% 1.257644 8221 -2.5486 11.06% 1.25297 8048 -2.5486 19.01% 2.881388													
7227 6.050026 44.46% 0.888337 7024 0.0434 61.84% 0.84589 3054 0.0109 294.89% 0.562407 2202 0.01019 241.83% 0.562407 2202 0.01019 241.83% 0.562407 4174 0.06414 34.82% 0.555489 6786 0.1853 17.15% 0.51037 2067 0.12003 18.02% 0.555489 2067 0.12003 18.02% 0.555489 1216 0.45584 8.56% 0.5627437 7442 0.73148 8.56% 0.5627437 7442 0.73148 8.56% 0.566841 7442 0.73148 8.56% 0.256841 7442 0.73148 8.56% 0.256841 7442 0.73148 8.56% 0.785025 5687 1.2652 0.66% 1.257844 8271 2.5489 11.08% 3.002211 84 4 cretes et 100 calculations per cycle.		0.86904	-0.65963	4.46%	0.07158	0.052824	36.51%	1 :	0.0617417	4.00%	4.69% 174.06918	175.42145	8.77.0
7024 0.0434 61.84% 0.84569 2024 0.0100 284.80% 0.625608 2022 0.01010 284.80% 0.62544 2022 0.01010 241.80% 0.565744 2174 0.06414 34.82% 0.555480 0972 0.12003 18.02% 0.555480 0972 0.12003 18.02% 0.555480 2067 0.12003 18.02% 0.55770 2067 0.12003 18.02% 0.55770 2067 0.12003 18.02% 0.55770 2067 0.12003 18.02% 0.55770 2067 0.12003 19.02% 0.55770 2067 0.12003 19.02% 0.557644 2521 1.2652 0.06% 1.257644 2521 1.2652 0.06% 1.257644 2521 1.2652 0.06% 1.257644 2521 2.5486 11.06% 1.215287		-0.06442	-0.636796	4.01%	0.07227	0.050028	44.46%		0.6407518	4.31%	173.78224	175,52214	200
2024 0.0342133 81.63% 0.626508 0.202407 0.2022 0.01616 241.63% 0.562447 0.55248 0.04174 0.00612 47.62% 0.55348 0.052248 0.0072 0.12003 18.02% 0.55348 0.0072 0.12003 18.02% 0.55348 0.0072 0.012003 18.02% 0.55348 0.02087 0.0238 17.16% 0.511037 0.0218 0.0238 17.16% 0.511037 0.0218 0.0238 17.16% 0.511037 0.0218 0.0238 0.000% 0.25384 17.00% 0.527437 0.1218 0.04584 1.257844 1.25524 1.2		-0.84216	-0.81998	3.58%	0.07024	0.0434		0.64599	0.6214972	3.94%	3.94% 173.75778	175.9957	127%
2024 0.0109 204.80% 0.562407 2202 -0.01616 241.85% 0.565744 2564 -0.046026 47.82% 0.555468 6726 -0.06414 34.82% 0.554606 6726 -0.16532 17.15% 0.515703 2007 -0.12003 19.02% 0.515703 2007 -0.2369 13.01% 0.511037 7004 -0.339 13.01% 0.510778 2007 -0.2369 13.01% 0.527437 1216 -0.45564 9.56% 0.765035 6887 -1.2652 0.060% 1.257644 8221 -2.5496 11.06% 3.002211 44 4 cycles of 100 calculations per cycle. 1974 -1.2652 5.36% 1.215207		-0.62342	-0.603148	3.36%	0.06214	0.0342133	81.63%	i i	0.604118	3.71%	3.71% 174.30779	176.75341	1,38%
2202 0.01616 241.83% 0.56576 4774 0.06414 34.82% 0.555486 6786 0.068674 24.49% 0.524806 0972 0.12003 18.02% 0.515703 2087 0.12003 18.02% 0.507778 2087 0.12003 18.02% 0.507778 1216 0.45584 8.56% 0.565743 1216 0.45584 8.56% 0.568841 7442 0.73746 8.56% 0.76505 5687 1.2652 0.66% 1.257844 8231 2.5486 11.06% 3.002211 1874 1.12652 5.36% 1.215287		4.59084	-0.57477	280%	0.043054	0.0108		0.582407	0.5748733	3.05%	175.83227	3.06% 175.83227 178.81357	1.72%
3584 -0.046026 47.82% 0.54678 4174 -0.06414 34.82% 0.536488 9972 -0.12003 18.02% 0.516703 2067 -0.12003 19.02% 0.511037 2067 -0.2369 13.01% 0.511037 7904 -0.3131 11.20% 0.527437 1216 -0.45564 8.56% 0.786641 5687 -1.2652 0.066% 1.257644 8271 -2.5466 11.06% 3.002211 844 -1.2652 0.066% 1.257644 8271 -2.5486 11.06% 3.002211 84 -1.2652 0.366% 1.25764 854 -2.5486 12.07% 2.861367		-0.56528	-0.55196	2.43%		-0.01616	241.83%	0.565744	0.5520966	2.47%	2.47% 177.87814	181.6773	220%
4174 - 0.06414 34.82% 0.555486 6786 -0.12003 19.02% 0.5574806 2067 -0.12003 19.02% 0.515773 2067 -0.2369 13.01% 0.511037 7004 -0.3131 11.20% 0.527437 1216 0.45564 9.58% 0.58691 7442 -0.73746 8.55% 0.785035 5687 -1.2552 0.80% 1.257644 8221 -2.5486 11.08% 3.002211 44 4 cycles of 100 calculations per cycle.		-0.54524	-0.53296	2.30%	-0.023584	-0.045026	47.82%		0.5348588	2.04%	182.47675	184.82905	127%
978 - 0.18874 24.49% 0.524606 9872 - 0.12003 18.02% 0.515703 2087 - 0.2389 13.01% 0.511037 2087 - 0.2389 13.01% 0.527437 1218 - 0.45684 8.58% 0.586841 7442 - 0.73746 8.58% 0.785035 5887 - 1.2652 0.06% 1.257844 8221 - 2.5486 11.08% 3.002211 44 c.yclar of 100 calculations per cycle.		-0.53384	-0.52034	2.59%	-0.04174	-0.06414	34.92%		0.5242782	2.13%	184.47076	2.13% 184.47076 187.02715	1.37%
0972 -0.12003 18.02% 0.515703 2096 -0.16532 17.15% 0.517703 2004 -0.3131 11.20% 0.527437 1216 -0.45584 8.58% 0.586941 7442 0.73746 8.55% 0.785035 5687 -1.2652 0.66% 1.257844 8221 -2.5496 11.08% 3.002211 44 cycles af 100 calculations per cycle.		-0.5204		2.03%		Ľ	24.49%		0.5178978	1.30%	187.42943	189.08348	1,35%
2067 - 0.18532 17.15% 0.507779 2067 - 0.2369 13.01% 0.511037 7804 - 0.3131 11.20% 0.527437 1216 - 0.45564 9.56% 0.586941 7442 - 0.73746 8.55% 0.785035 5687 - 1.2652 0.86% 1.257644 8221 - 2.5486 11.06% 3.002211 44 cycles of 100 calculations per cycle. 1874 - 1.2652 5.36% 1.215287 8049 - 2.5486 18.01% 2.881388		-0.50646	-0.497256	1.85%	-0.0972		18.02%		0.5115376	0.81%	0.81% 190.86413	163.57073	1.40%
2087 - 0.2389 13.01% 0.511037 1218 - 0.45584 8.56% 0.586241 7442 - 0.73746 8.55% 0.785035 5887 - 1.2652 0.86% 1.257844 8221 - 2.5486 11.06% 3.002211 44 crycles of 100 calculations per crycle. 1874 - 1.2652 5.36% 1.215287 8048 - 2.5486 18.01% 2.881388		-0.48896	-0.4808	1.70%		-0.16532	17.15%		0.5084283	0.13%	0.13% 195.64781	198.9752	1.67%
7804 - 0.3131 11.20% 0.527437 1216 - 0.45584 8.58% 0.586941 7442 - 0.73748 8.58% 0.785035 8251 - 2.5486 11.08% 3.002211 4 crease of 100 calculations per cycle. 1974 - 1.2652 5.38% 1.215287 8048 - 2.5486 18.01% 2.881388		-0.46648	-0.4575	1.96%	-0.2087	-0.2389		L	0.5165833	1.07%	204.10342	207.67124	1.72%
1216 0.45584 8.58% 0.586841 7442 0.73746 8.55% 0.785035 5687 1.2652 0.86% 1.257644 8221 2.5486 11.06% 3.002211 44 cycles of 100 calculations per cycle. 1874 1.2652 5.36% 1.215297 8049 2.55496 18.01% 2.861368		-0.4482	-0.43706	2.55%		-0.3131	11.20%		0.5376365	1.90%	211.81332	1.80% 211.81332 215.81886	1.76%
7442 0.73746 8.55% 0.785035 5687 -1.2652 0.66% 1.257644 8221 -2.5486 11.06% 3.002211 44 crycles of 100 calculotions per cycle. 1874 -1.2652 5.36% 1.215287 8048 -2.5486 18.01% 2.881388		-0.41768	-0.39804	4.98%	-0.41218	-0.45584	9.58%		0.605166	3.01%	3.01% 224.80517	228.8725	1.86%
8221 -2.5496 11.08% 3.002211 4.4 cycler of 100 calculations per cycle. 15784 12.852 13.002211 1874 -1.2652 5.36% 12.15287 12.8049 -2.5496 19.01% 2.881368		0.36116	-0.31314	15.33%	-0.67442	-0.73748	8.55%		0.8011891	4.51%	241,83042	4.51% 241.83042 246.98297	2.00%
44 cycles of 100 calculations per cycle. 44 cycles of 100 calculations per cycle. 1974 - 1.2652 5.36% 1.215287 1.2646 19.01% 2.861368	4 0.5	0.04413	-0.0583	25.59%	1,25687	.1.2652			1.2665889	0.71%	287.98929	287,31651	0.25%
4 4 cycles of 100 calculations per cycle. 1674 - 1.2652 5.36% 1.215287 8049 - 2.5486 19.01% 2.881368	0.25	0.006234	1.090012	8.60%	_	.2.5496	11.08%		2.77283	8.27%	289.38009	8.27% 289.38009 293.14781	1.20%
1674 - 1.2652 5.36% 1.215287 8048 - 2.5486 18.01% 2.881388	is above for Kp of 4	and 8 wer	e calculated	using 200 p.	nack and 4 cy	riches of 100 ca	alculations p	er cycle.					
0.25 0.56564 1.090012 48.11% -2.5049 -2.5466 19.01% 2.861368	w calculations were	done with	75 panets an	of 3cyc of 60	Scales								
0.25 0.50504 1.000012 48.11% -2.5049 -2.5406 18.01% 2.881308		-0.2078	-0.0593	250.42%	-1.1874	-1.2652	5.36%		1.2885889	4.06%	260.15479	4.05% 280.15479 267.31851	2.68%
		0.56564	1.000012	48.11%		.2.5496			2.77283	3.10%	281.40143	3.19% 281.40143 293.14781	4.01%

TABLE 2.4 6.7 DEGREE PITCH CL COMPARISON

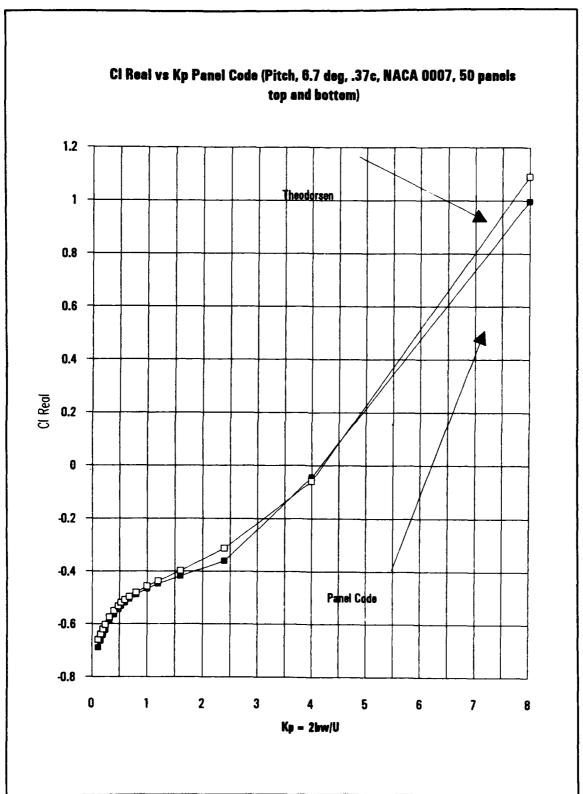


Figure 2.21 6.7 degrees pitch C_L Re

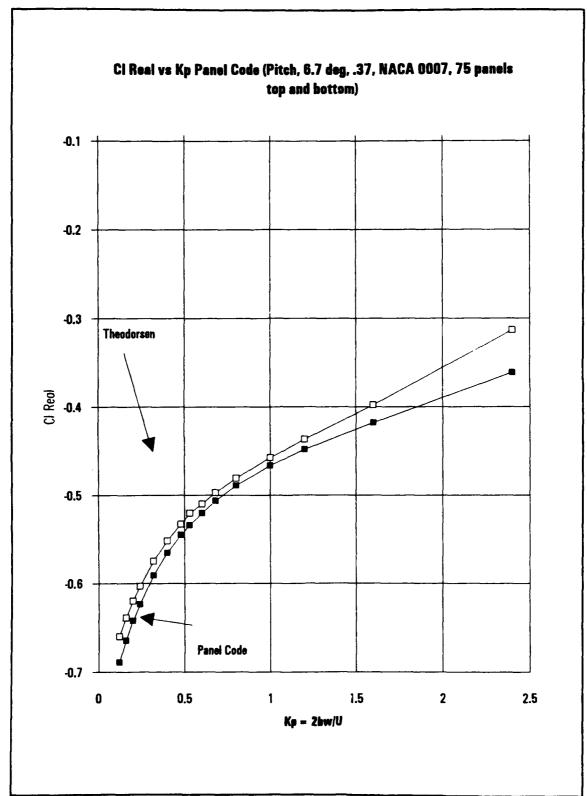


Figure 2.22 6.7 degrees pitch C_L Re

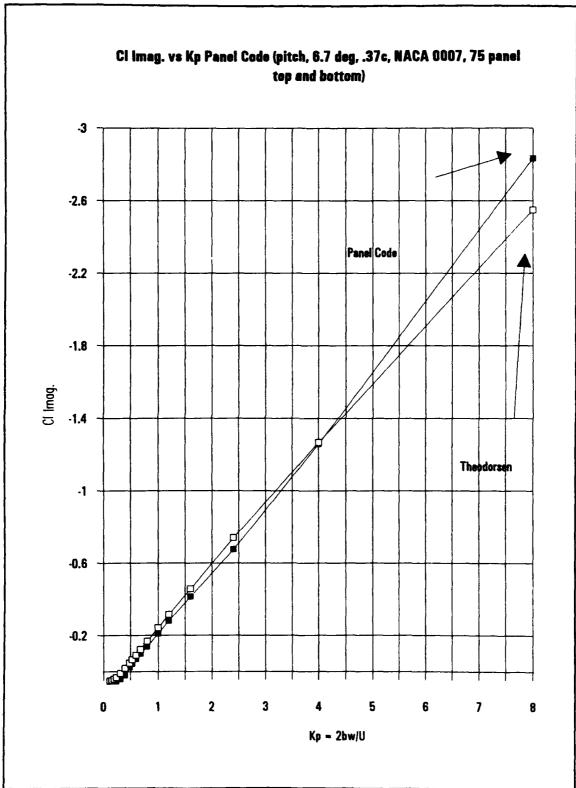


Figure 2.23 6.7 degrees pitch C_L Im

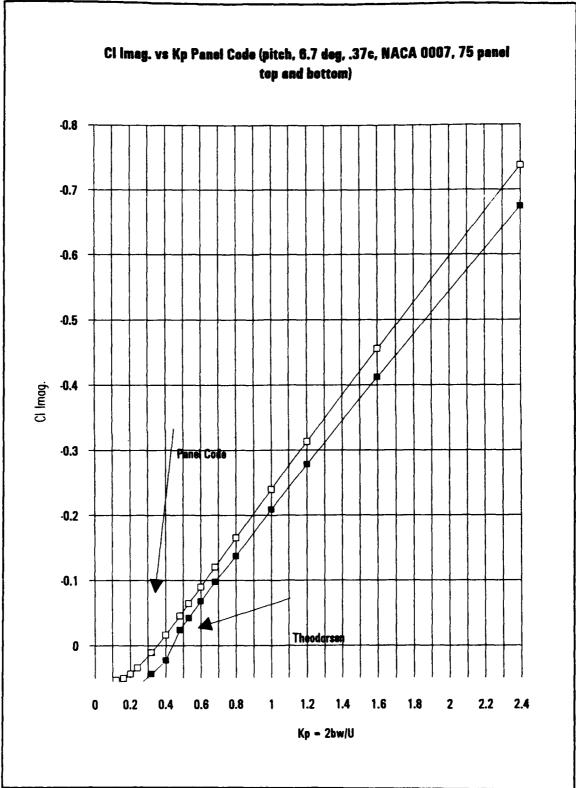


Figure 2.24 6.7 degrees pitch C_L Im

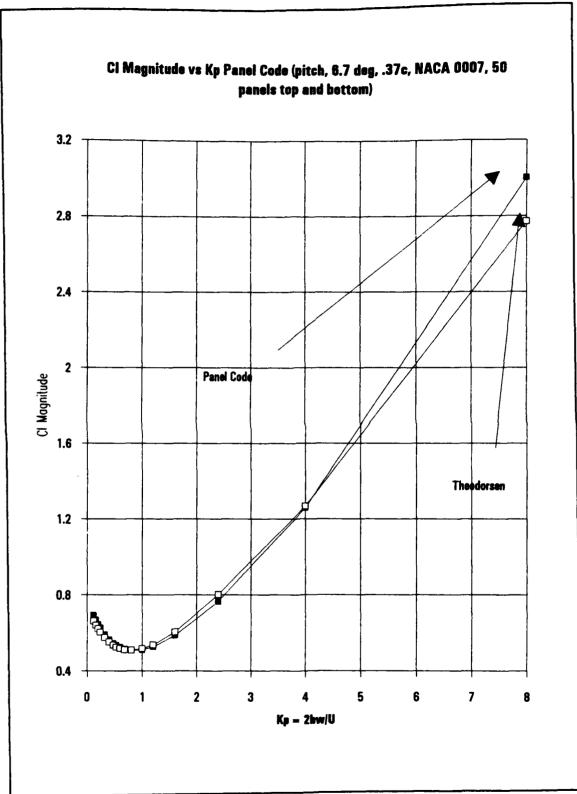


Figure 2.25 6.7 degrees pitch C_L Magnitude

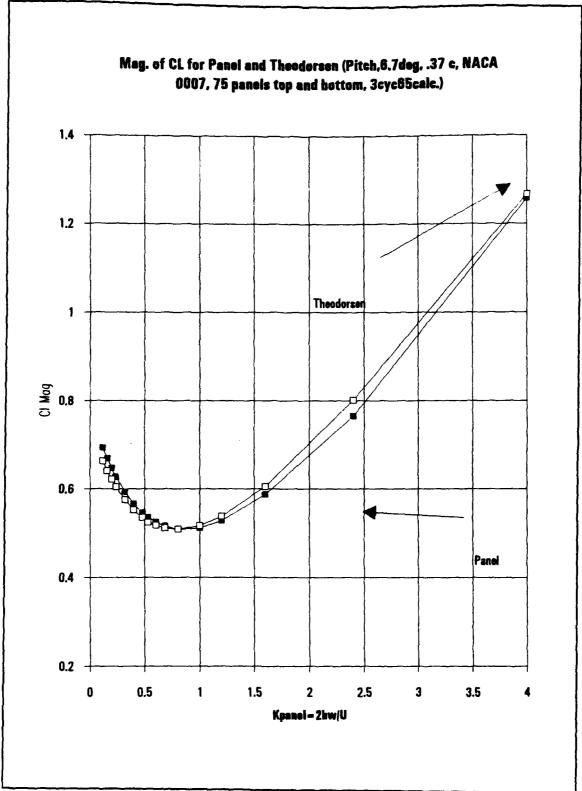


Figure 2.26 6.7 degrees pitch C_L Magnitude

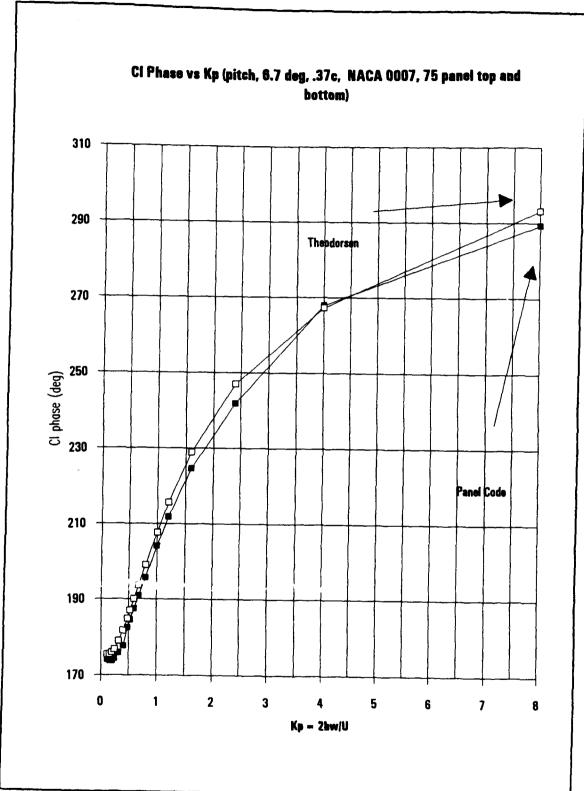


Figure 2.27 6.7 degrees pitch C_L phase

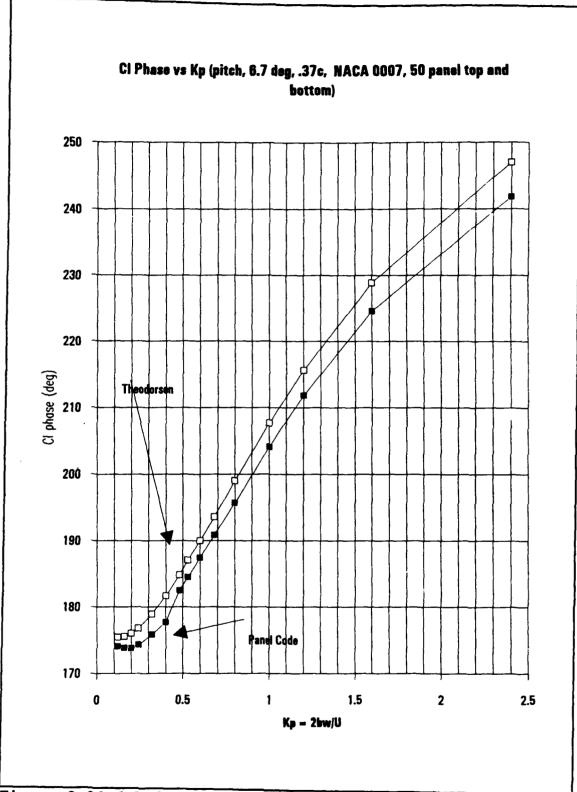


Figure 2.28 6.7 degrees pitch C_L Phase

	Comparison	Comparison of Panel Morne	12	namic Value	(CM) with	nt Aerodynamic Values (CM) with Theordonaen Re	Results						
		(phtch, 6.7 deg	خه ا	37c, NACA 0007, 50 penele		top and bottom, 3cyc66calc.)	n. 3cyc66calc	7			.		
	Kpenel lequ	Kpenel lequel to $2 \times $ Theore	iordonen Kt)					- 1					
1/kt	Kpenel	2	E	* 0.11	Imeg Pen.	The Th	× OFF	Meg Pen.	Mag The	* 011	F 88		10 %
10.07	90010	0.070057	0.070222	0.32%	-0.018262	0.017304	5.48%	0.081136	0.081188	90.0	247	347.0038	0.20%
12.6	1	. I	٥	1.21%	-0.021798	1_	6.32%	I	•	0.70%	344	344.9450	0.27%
2		1	0	4.02%	-0.023347		0.97%	0.075553	0.078486	3.74%	341.9900	342.5107	0.15%
8.33		1	0	1.38%	-0.024826	-0.026148	5.05%	0.076256	0.077644	1.79%	341.0004	340.3203	0.20%
6.25	0.32	0.066532	0.07017	2.33%	-0.020115	0.030698	5.16%	0.07448	0.076691	2.78%	336.9821	336.3714	0.16%
9		0.065941	0.066094	3.16%	-0.032676	-0.034798	8.39%	0.073649	0.07647	3.82%	333.7106	332.032	0.23%
4.17	0.48	0.084013	0.000646	3.81%	-0.036849	-0.038681	7.32%	0.073367	0.076972	4.06%	330.7498	329.8319	0.26%
3.76	0.63	0.063066	0.00584	4.23%	-0.037946	_	7.95%		0.07768	5.26%	328.9600	327.9488	0.31%
3.33	0.6	0.062071	0.066418	6.11%	-0.040477	-0.044321	8.67%		0.078016	6.22%	326.8914	326.8817	0.31%
2.04	0.68		0	6.95%	-0.043606		0.24%	-4	I	7.10%	324.5641	323.684	0.30%
2.5	0.8		0.065184	8.89%	o		10.02%	-4	_]	8.20%	321.4786	ı	0.28%
7	-	0.080704		8.86%	-0.0662		10.87%	_	0.001714	8.00%	317.2064		0.20
1.67	1.2	0.061886	0.068032	10.34%	-0.084202		11.62%	_	9.100200	11.01%	313.9523	313.6416	0.13%
1.26	0.	0.066935	0.077741	13.90%	-0.08115	-0.092240	12.03%	0.106193	ı	12.80%	309.5167	310.1219	0.20%
0.83	2.4	0.084477	0.10472	19.33%	-0.117642	-0.117642 -0.132633	11.38%	0.14475	J	14.34%	306.7047	308.2827	9.0
0.6	4	0.163099	0.19447	16.13%	L	-0.21796 -0.215551	1.12%	0.272228	0.290311	6.23%		312.0668	- 88
0.25		8 0.534359	0.018634	13.82%	_	-0.52513 -0.428778	22.47%	0.7492	0.752699	0.46%	315.4991	326.2741	3.01%
ues for	to equal to	Values for Kp equal to 4 and 8 above w	e were celcul	lated using 2	OO penels to	ere calculated using 200 panels top and bottom	n and 4 eyel	and 4 cycles of 100 calculations	lculations.		**		
woled	Values were	The below values were calculated using	aing 75 penels	e and 3 eye of 66 calc	of 86 celc.							- 1	
9.6	-3	4 0.144459		l	26.72% -0.200637	-0.215551	6.97%		0.290311	14.87%	306.7876		2.02%
0.25		0.448235	ြ	27.54%	-0.496666	27.54% -0.495585 -0.428778	15.58%	0.668221	0.752699	11.22%	312.128	325.2741	4.04%

TABLE 2.5 6.7 DEGREES PITCH C_M COMPARISON

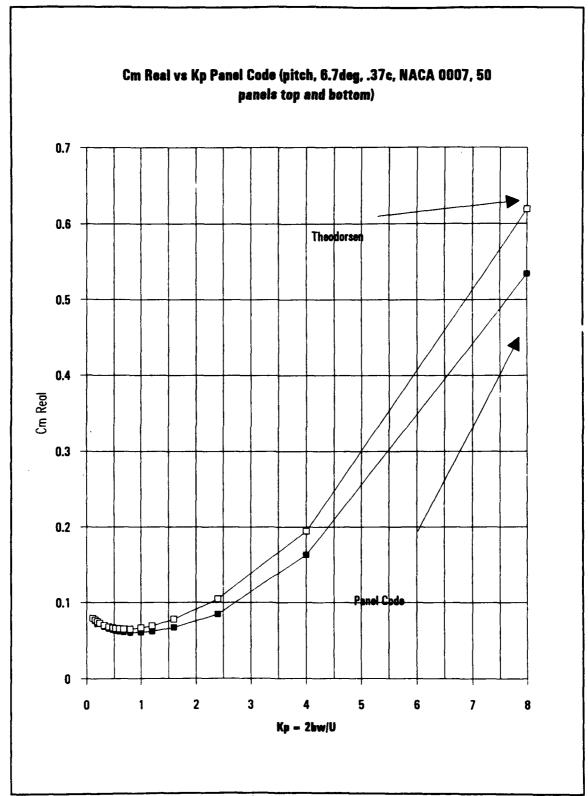


Figure 2.29 6.7 Degrees pitch C_M Re

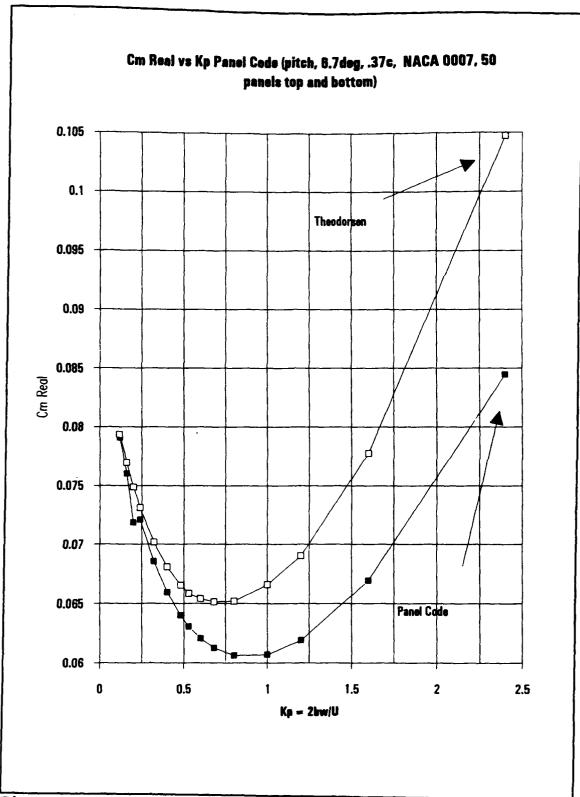


Figure 2.30 6.7 Degrees pitch C_M Re

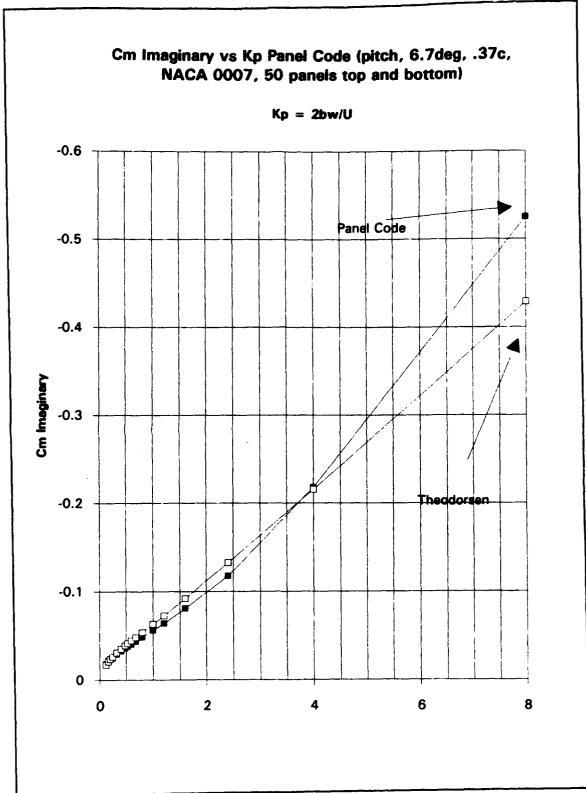
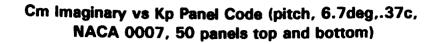


Figure 2.31 6.7 Degrees pitch C_M Im





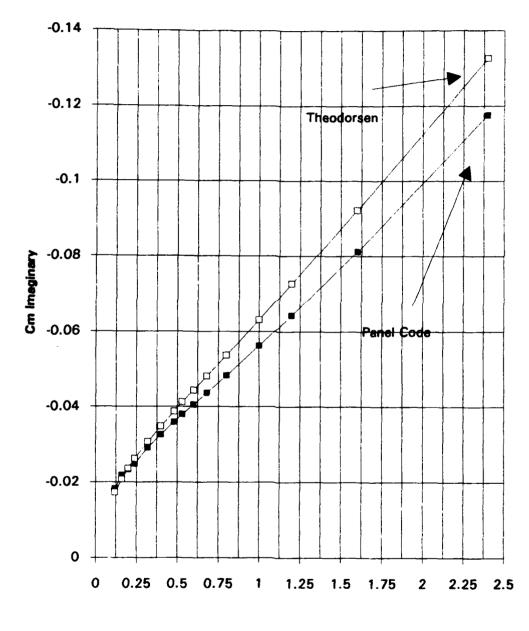


Figure 2.32 6.7 Degrees pitch C_M Im

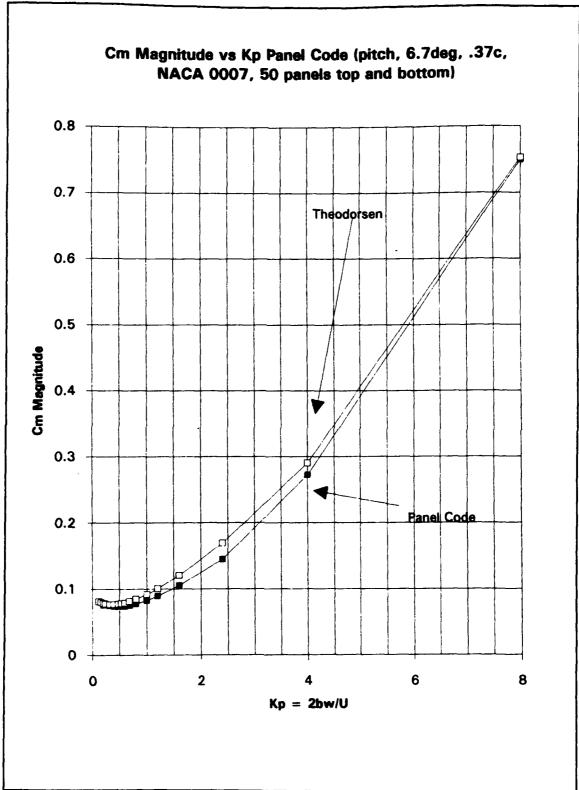


Figure 2.33 6.7 Degrees pitch C_M magnitude

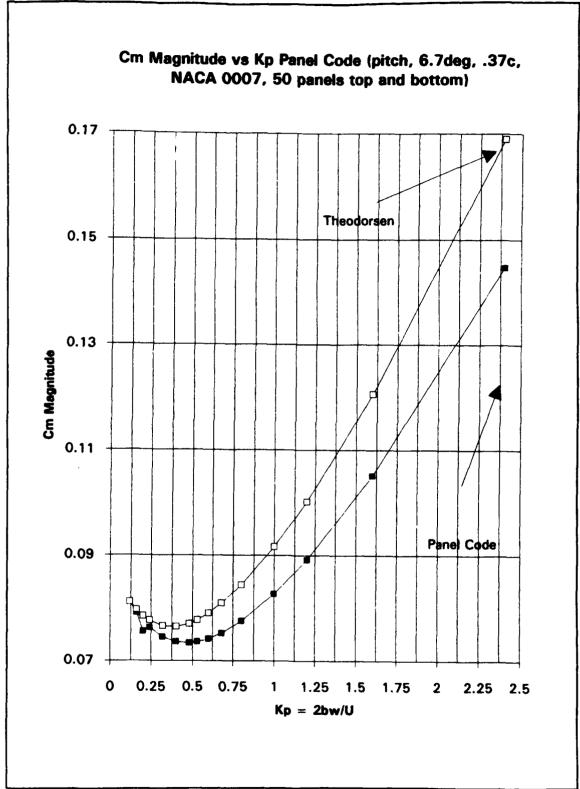


Figure 2.34 6.7 Degrees pitch C_M magnitude

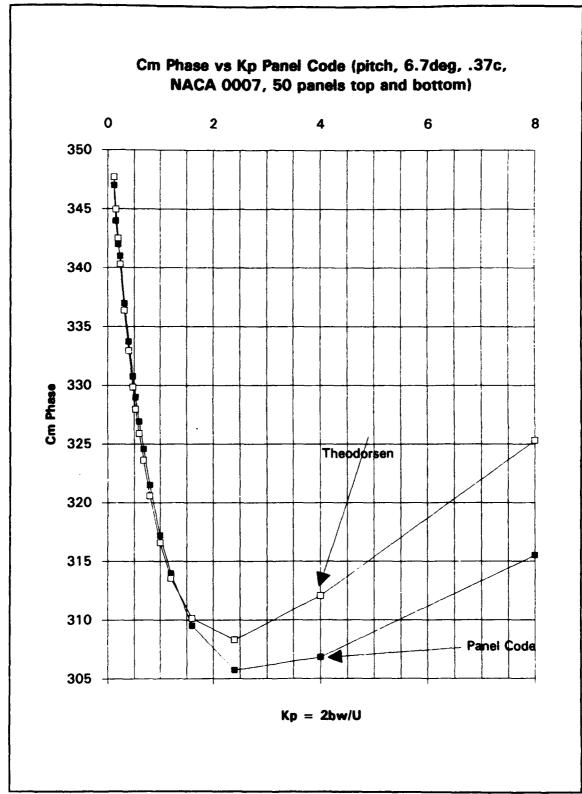


Figure 2.35 6.7 Degrees pitch C_M phase

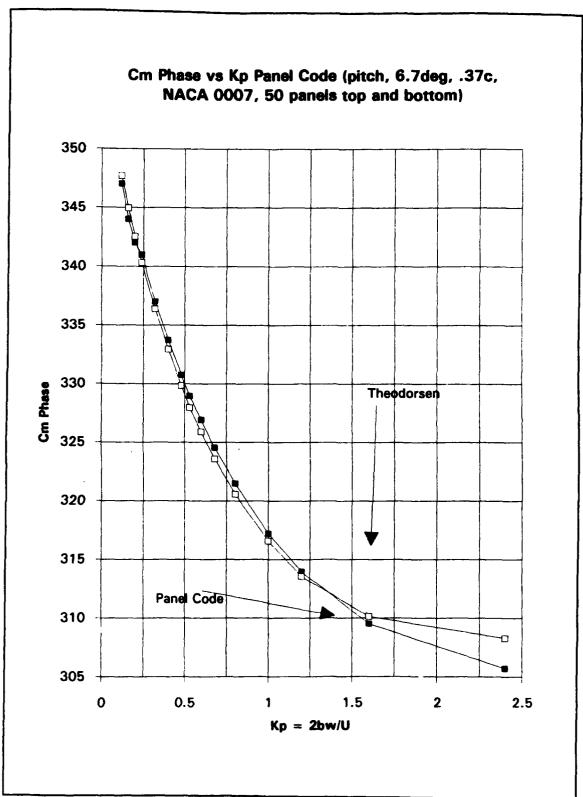


Figure 2.36 6.7 Degrees pitch C_M phase

			(plumps .0831	(plumps .0833h/2b, .57c, NACA 0007, 76 pensis,3 oyed6;	MCA 0007.	Man Comment of	2	•					
			Kperrel tequal to 2 x Theordoneen Kt)	to 2 x Theory	tensen Kı)		SEDIFF taken wrt Theorderen values	mt Theordered	n vatues.				
1/kr Ke	Keene	Per per.	feet theo.	% DPF.	Imag Pan.	imeg Theo.	% DIFF.	May Pen.	Mag Theo.	& DIFF.	Pass P.	Pass 7.	% OFF.
-													
16.67	0.11866	0.0064	0.007068	20.81%	0.06864	0.066004	4.71%	0.066266	0.06644837	4.00%	201.714	262.908	0.42%
12.5	0.16	-0.01294	-0.010103	22.18%	-0.07612	-0.0720618	4.26%	0.076127	0.07276081	4.03%	260.6713	282.0184	0.61%
10	0.2	-0.0166	-0.0128	24.22%	97080'0	0.0871	3.86%	0.001888	99000000	4.36%	280.0332	261.6366	% 10.0
6.33	0.24	10.0100	-0.016088	26.10%	0.10484	-0.101284	3.61%	0.108663	0.108863 0.10240164	4.16%	260.7163	261.6271	0.00%
8.26	0.32		-0.016022	31.73%	0.13164	-0.1277672	3,04%	0.133764	0.133764 0.12602207	3.07%	256.7771	261.8706	0.84%
•	9.0	-0.02006	-0.01864	40.87%	-0.16626	-0.15232	2.80%	0.188421	0.188421 0.18344417	3.24%	280.5246	263.0802	260
4.17	97.0	-0.02802	0.016841	26.36%	-0.1786	-0.17868	2.23%	0.181376	0.17838686	2.84%	261.762	264.6868	1.07%
3.76	0.63	-0.02476	-0.014062	78.21%	-0.18348	-0.18666	3.00°C	0.196068	0.1804082	2.44%	262.7074	266.7678	1.16%
3.33	90	-0.02164	-0.008186	134.60%	-0.2127	-0.20883	1.86%	0.213788	0.20803181	2.28%	284.2174	207.4816	1.22%
2.94	980	-0.016632	0.001331	1074.46%	-0.234043	-0.230234	1.06%	0.234664	0.234864 0.23023786	×99"-	266.1788	200,00%	1.20%
2.6	8.0	-0.00282	0.01466	110.21%	0.2666	-0.2617	1.48%	L	0.206886 0.20211141	1.33%	200.3016	273.2106	1.40%
~	-	0.02874	0.06196	44.71%	-0.31742	-0.31284	1.43%	0.318718	0.318718 0.31722782	0.47%	276.1736	278.4308	1.62%
1.67	1.2	0.07234	0.10188	28.99%	-0.36832	-0.36362	1.60%	0.376336	0.376338 0.3776266	218	281.0824	286.866	1.60%
1.26	1.6	0.18372	0.23742	10.41%	-0.47526	-0.48404	2.42%		0.513243 0.52124662	1.64%	282.1764	267.086	1.06%
0.83	2.4	0.68614	0.8436	8.91%	0.000462	-0.00572	3.11%		0.90285 0.82588186	2.61%	310.483	314.0277	1.13%
0.6	•	1.86.06.1	1.87276	8.96%	-1.20784	1.07178	12.00%	2.213438	2.24610454	1.41%	326.8286	331.4862	1.37%
0.25	•	8.013278	8.24664	2.83%	-3.3862	-2.1084	60.63%	0.000366	8.666386 8.61243724	2.20%	337.0824	346.8626	2.48%
Vailuse for Kp equal to 2.4,4, and	quel to 2.4,	•	Acre were calcul	ated using 20	O permis top	eleulated using 200 penals top and battom and 4 oyessa of 100 saloulations	4 overes of 10	O enfortements					
The values balow were es	TAY WEND BE	gries bestero	76 persels are	76 parete and 3 eye Geate	نو				-				
0.83	2.4	0.50626	0.6435	12.00%	-0.7011	-0.00672	8.21%	0.901217.	0.801217- 0.82888188	2.06%	308,9269	314.0277	1.62%
9.0	•	1.80644	1.87278	8.33%	-1.2444	1.07178	16.11%	2.106218	2,186218 2,24510464	2.22%	325.4679	331.4062	1.82%
0.26	•	7.82628	8.24664	6.10%	-3.62086	-2.1084	\$10.00	8.66179	8.61243724	0.81%	336.7781	345.0626	2.80%
1													
						***************************************			-				
2	1	1	Tag Par	Imag Theo.									
			-										

TABLE 2.6 PLUNGE h/2b=.0833 C_L COMPARISON

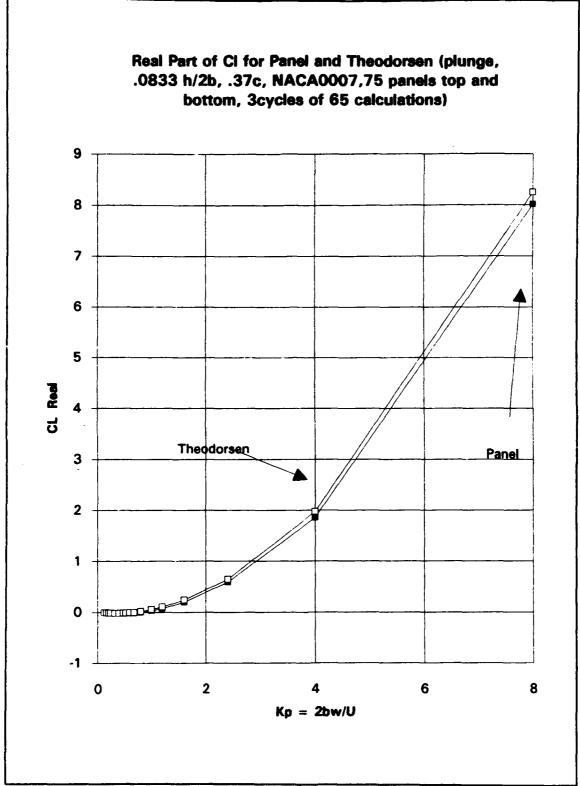


Figure 2.37 Plunge h/2b=.0833 C_L Re

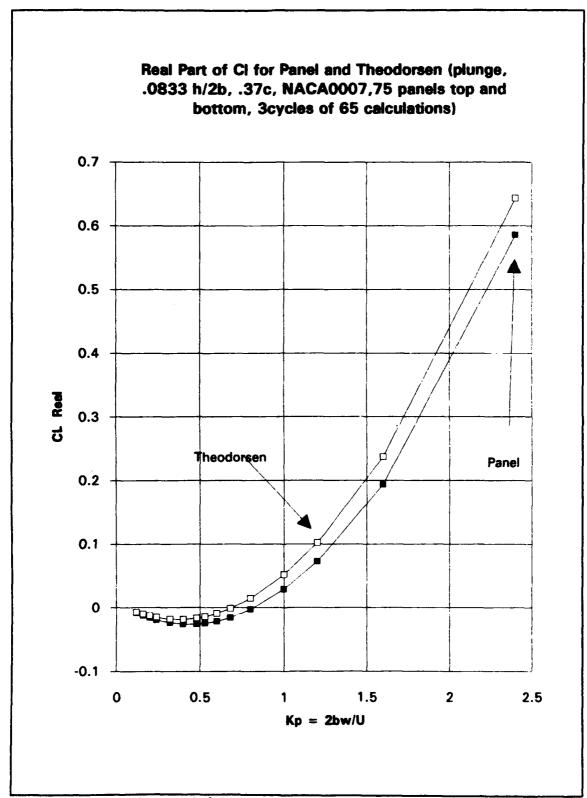


Figure 2.38 Plunge h/2b=.0833 C_L Re

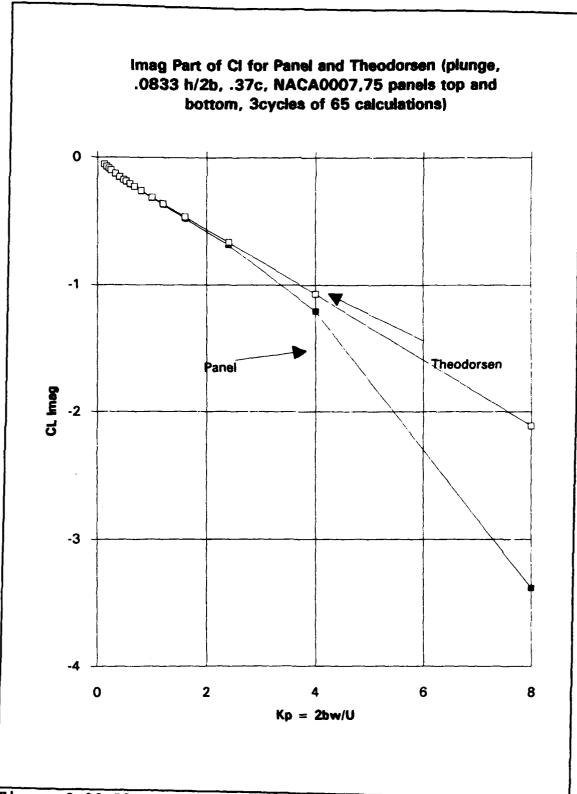


Figure 2.39 Plunge h/2b=.0833 C_L Im

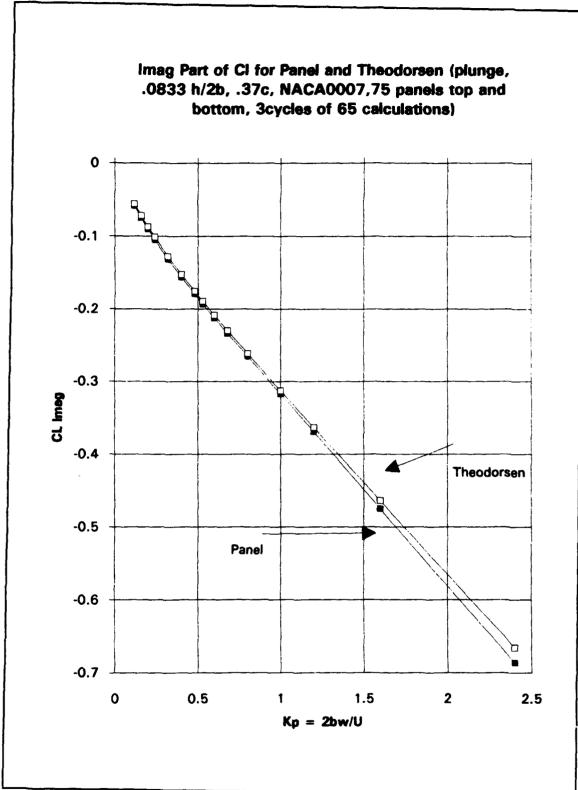


Figure 2.40 Plunge h/2b=.0833 C_L Im

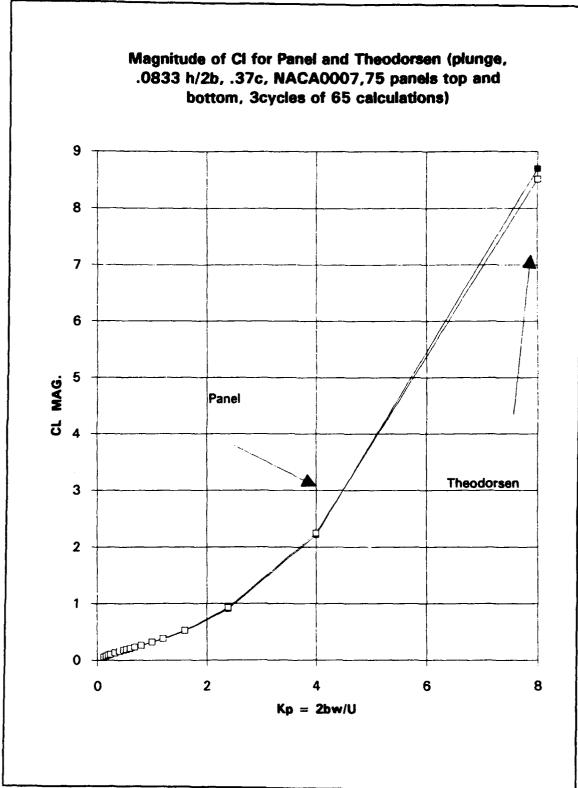


Figure 2.41 Plunge h/2b=.0833 C_L Magnitude

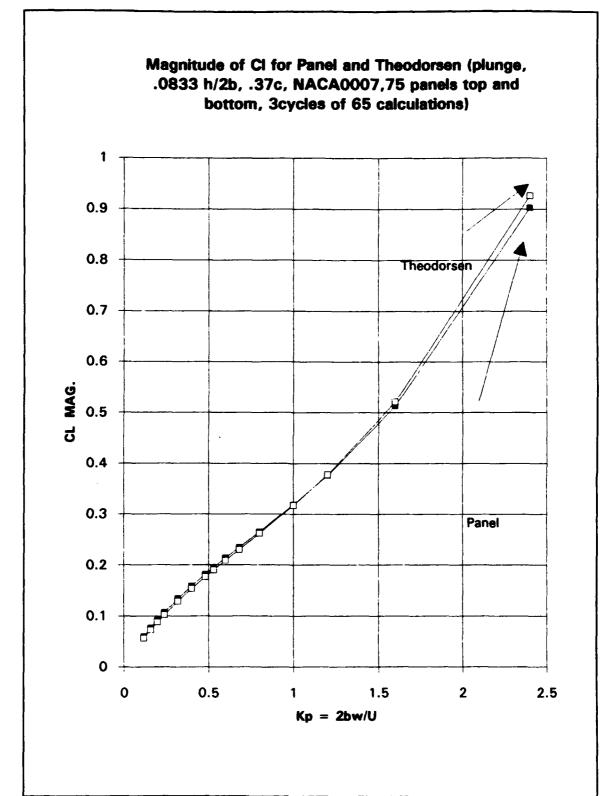


Figure 2.42 Plunge h/2b=.0833 C_L magnitude

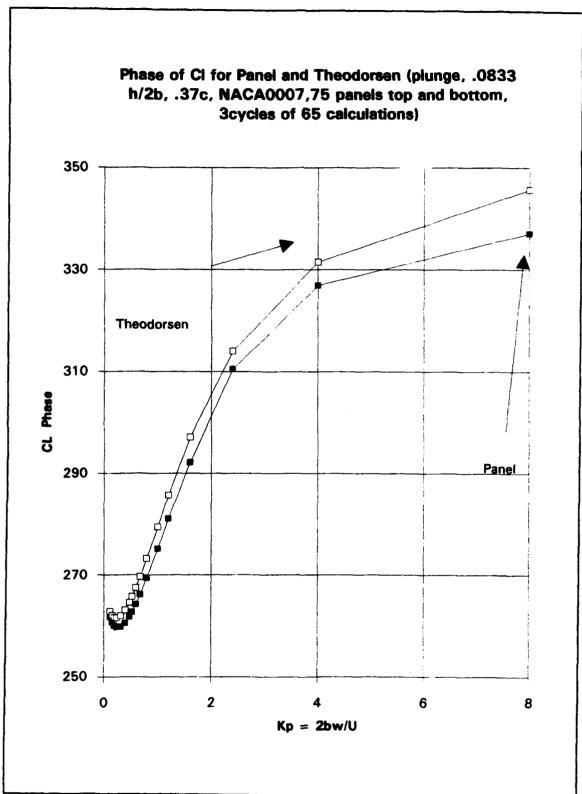


Figure 2.43 Plunge h/2b=.0833 C_L phase

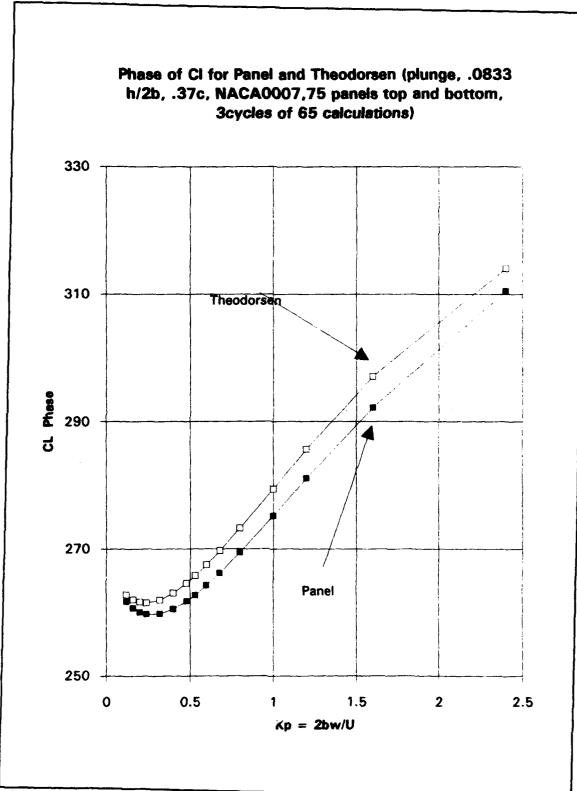


Figure 2.44 Plunge h/2b=.0833 C_L phase

				Comparation of These	expansion of Finns (.m Value (Plungs) with Theoretonean Restuits	o with the	Ordorpen Rosa	917			- 1				
				(plungs .0633b/b, .3	unge .06336/b, .37e, NACA 0007, 75 pensels,3 cyc65)	pensis,3 o	(Spor	·					<u></u>		
				Kpanel (equal to	panel (equal to 2 x Theordonen Kt)	K			%DIFF taken	%DIFF taken wrt Theordorsen values	n values.		_		
						_									
<u> </u>		Kpancel	Real pan.	Real pan. Real theo.	& DIFF.		Ing Pas	Ineg The	% DIFF.	Mag Pan.	Mag Theo.	% DIFF.	Ples P	Place Ph Phase Thi % DIFF	F DIFF
	16.67	0.11998	16.67 0.11998 0.00132	0.001319179		8900	0.00675	0.006751 0.006721	0.44%		0.00687786 0.00684878	0.43	K 78 0351	78 2044	0.058
	12.5		0.16 0.00202	0.00204733		1.33%	0.00865	0.00865 0.008646			0.00888273 0.00888531			76.6783	23.8
	101	0.2	0.00276	0.002844726		2.98%	0.01042	0.01042 0.010451	_		3 0.01083124		0.48% 75.1645 74.7732	74.77321	0.52%
	8.33	0.24	0.24 0.00354	0.00369484		4 19%	0.01209	0.01209 0.012145		0.45% 0.01259761 0.01269456	1 0.01269456		0.76% 73.6798 73.0788	73.0788	0.82%
	6.25	0.32	0.32 0.00516	0.005512253		6.39%	0.0152	0.0152 0.015331		0.85% 0.01605197 0.01629167	7 0.01629167		6 71.249	71.249 70.2237	1.46%
	2	4.0	0.4: 0.00683	0.00745976.		8.44%	0.01807	0.01807 0.018279	1.14%		0.01931771 0.01974283	2.15%	6 69.2947	67.7996	2.21%
 	4.17	ĺ	0.48 0.00857	0.009533759		10.11%	0.02081	0.02081 0.02107	1.23%		0.02250558 0.02312655	2.69%		67.6171 65.6542	2.99%
	3.75		0.53 0.0097	0.01098723		11.72%	0.02247	0.02247 0.022787		1.39% 0.02447429	0.02447429 0.02529756		66.6508	20,20	3.72%
	3.33	9.0	0.6 0.01134	0.01287852		11.95%	0.02475	0.02506		1.24% 0.027224221 0.02817525	21 0.02817525			62.800	4.11%
	2.8	89 0	0 68 0.01328	0.01528568		13.10%	0.027295	0.027295 0.027628		1.21% 0.03035548 0.03157482	1 0.03157482		3.86% 64.0503 1 7.76	1000	4.92%
	2.51	0.8	0.81 0.01643	0.0191749		14.32%	0.03106	0.031061 0.031403		1.09% 0.03513785 0.03679467	5 0.03679467	4.50%	6 62.1222	62.1222 58.5917	6.03%
	71		11 0.02232	0.026475126		15.69%	0.03722	0.037221 0.037552	0.88%		0.04339943 0.04594666	8.54%	5 59.0498	54.8153	7.73%
	1.67	1	1.21 0.02915			16.43%	0.04331	0.04331 0.043623	0.72%		0.05220612 0.05585274	6.53%		\$6.0573 51.3552	9.16
	<u>x</u> .		1.61 0.04591	0.055251155		16.91%	0.05529	0.05529 0.055684	0.71%	% 0.07186593	1 0.0784436	_	8.39% 50.2955 45.2236	45.2236	11.22%
	0.83		2.4 0.09818			11.71%	11.71% 0.0800021 0.079887	0.079887	0.14%	$\lfloor \perp \rfloor$	0.1266481 0.13692186		7.50% 39.1748 35.6935	35.6935	9.75%
	0.5	7	4 0.26237			8.47%	8.47% 0.10952131 0.128854	0.128854	13.00%	_	0.28431041 0.31428687	9.54%	1 22.6372	22.6572 24.2042	6.39%
	0.25	ec	8 1.06271	1.10392		3.73%	3.73% -0.021611 0.253136	0.253136	\$601	1.062926	1.1325711	6.15%		12.915 109.02%	09.02
Value	for Kp e	qual to 2.	4.4.and 8	Values for Kp equal to 2.4.4, and 8 above were calculated using 200 panels top and bottom ad 4 cycles of 100 calculations	ated using 200 p	nacis top	and bottom	ad 4 cycle	s of 100 calcul	Phone.	-				
2	May wolt	a were a	The below values were calculated using	ing 75 panels and	75 pamels and 3 cyc of 65 cale.						-				
	0.83		2.4/ 0.09315			16.23%	0.07777	0.07777 0.079887	2.65%	Ĺ	0.121347 0.13692186		11.37% 39.8582 35.6935	35.6935	11.67%
	0.5	7	4 0.24712	0.28665824		13.79%	0.10401	0.10401 0.128854	19.28%	! —.	0.26811635 0.31428709		1 22.8257	22.8257 24.2042	\$.70%
	0.25	∞	0.9993	1.1039244		9.48%	-0.04788	-0.04788 0.253136	119%		1.00044639 1.13257539	11.67%	1 -2.7431	12.915 121.24%	21.24%
Kp of 4	4 and 8 f.	or CM in	Kp of 4 and 8 for CM img were redon		using h/b=.01, .02,.04,.06 to better understand why the imag values became so different	o better u	nde:stand v	vhy the im	ag values beca	se so different.					
986	values of	hb were	Those values of h/b were made smaller		to account for the very high Kp. (NACA 0007.100 panels. 3 cyc6537c)	P.(NACA	1 0007.100	panels.3cy	c6537c)						
-9	J. Imagil	b/b= 01. Imagilmag Th. %diff		h/b = .02. long p long Th	Imag Th.		%diff		h/b = .04. Imag p Imag Th.	P Imag Th.	%diff	h/b= 06, Image Image Th. %diff	Imag Th.	%diff	
	0.01536	0.01536 0.01546	0.65%	0.0304	0.	0.030937	1.74%		0.05862	62 0.06187		+	0.08291 0.09281	10.67%	
0	1027341	105020 0 145750 0	200	70070											

TABLE 2.7 PLUNGE h/2b=.0833 C_M COMPARISON

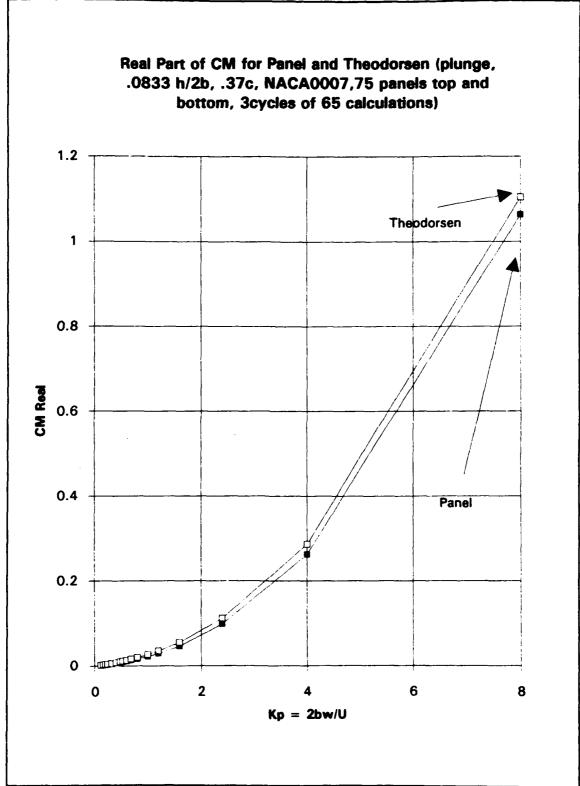
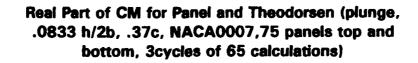


Figure 2.45 Plunge h/2b=.0833 C_M Re



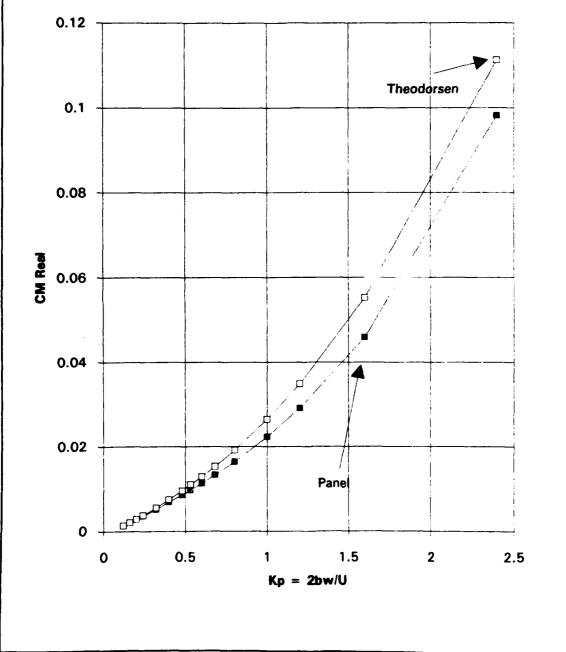


Figure 2.46 Plunge h/2b=.0833 C_M Re

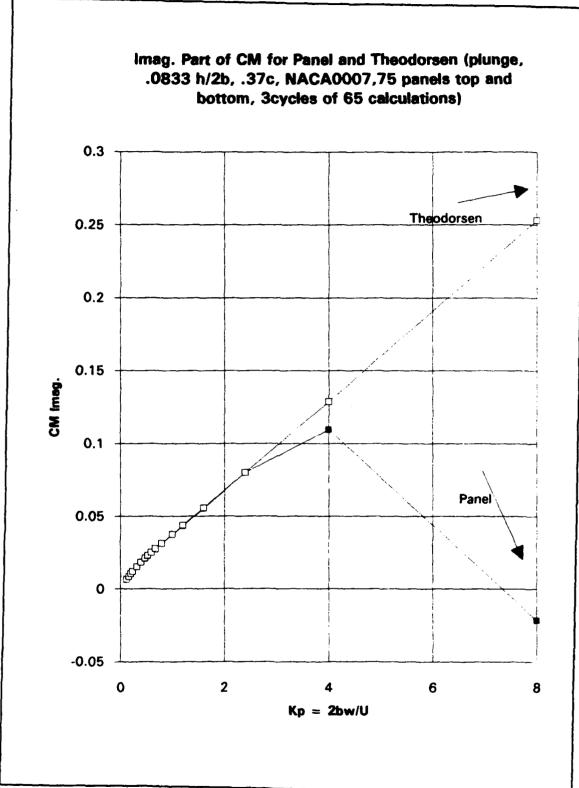
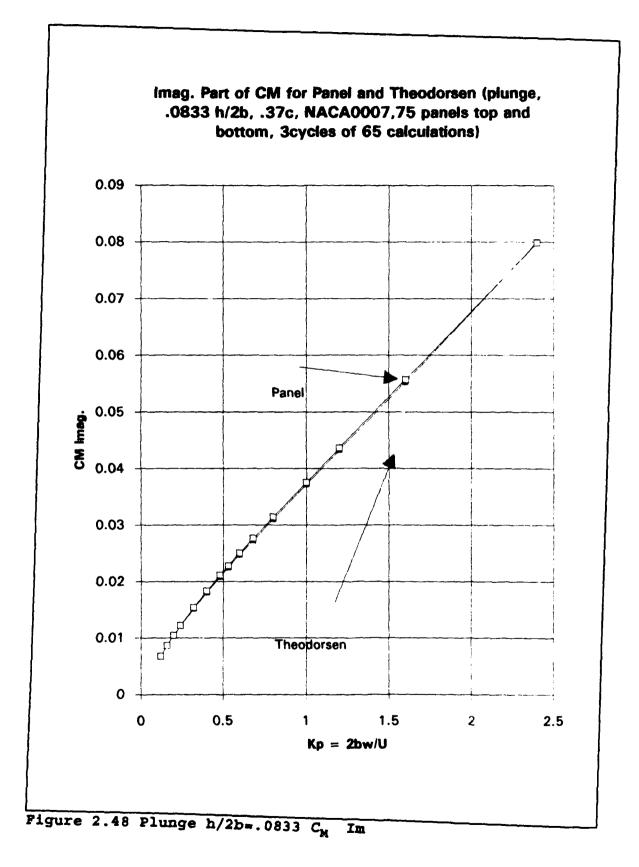


Figure 2.47 Plunge h/2b=.0833 C_M Im



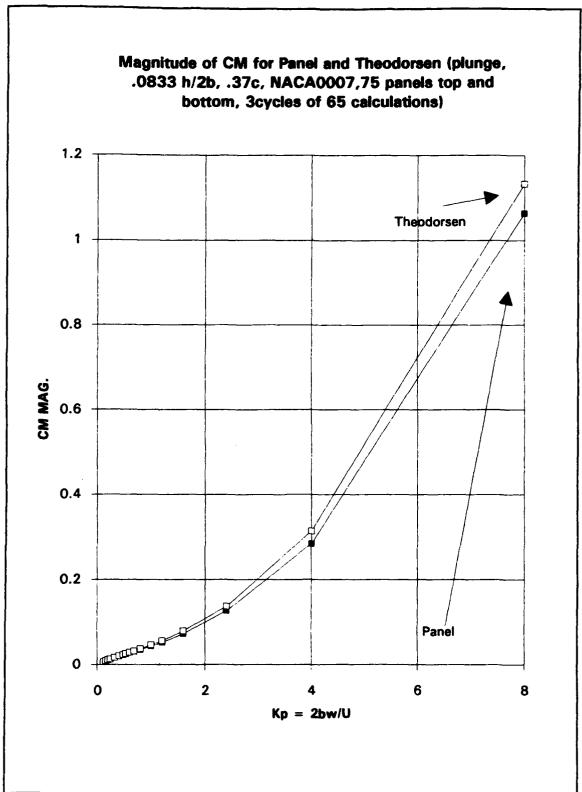


Figure 2.49 Plunge h/2b=.0833 C_M Magnitude

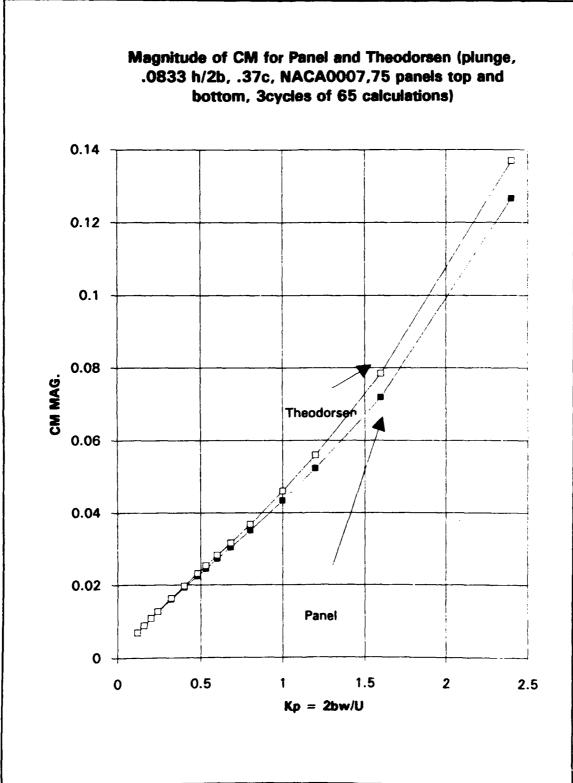


Figure 2.50 Plunge h/2b=.0833 C_M Magnitude

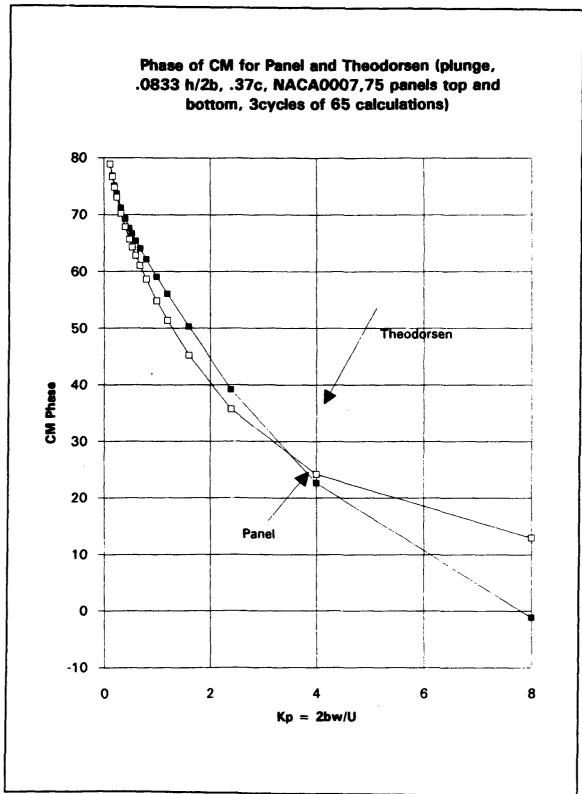


Figure 2.51 Plunge h/2b=.0833 C_M Phase

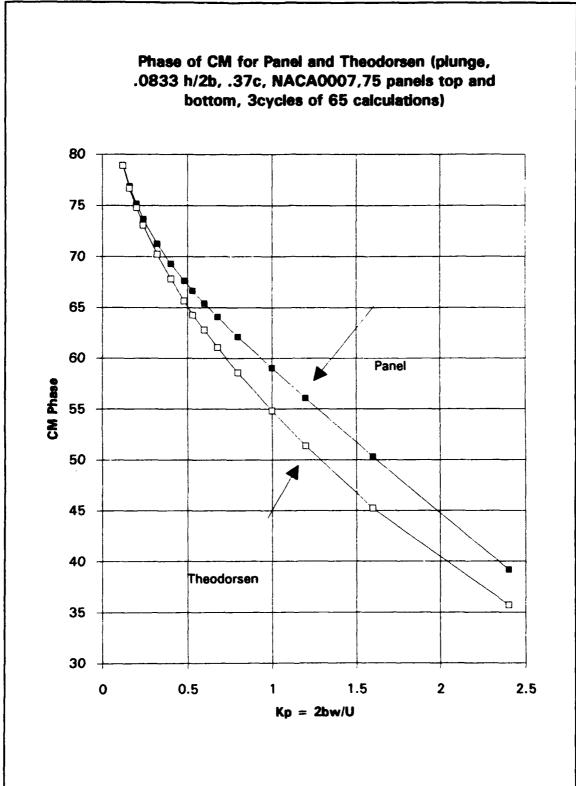


Figure 2.52 Plunge h/2b=.0833 C_M Phase

Pleate pen. Real theo. \$ DiFF. Img Pen Imag Theo. \$ DiFF. Mag Pen. Mag Theo. \$ DiFF. \$ DiFF. Mag Pen. Mag Theo. \$ DiFF. \$ DiFF. Mag Theo. \$ DiFF. \$ DiFF. Mag Theo. \$ DiFF. Mag Theo. \$ DiFF. \$ DiFF. Mag Theo. \$ DiFF. \$ DiFF. Mag Theo. \$ DiFF. \$ DIFF.			Comparison of	Sanel Cm V	Ptues (Ptu	nge) with Theo	Indones R	Beults					
Real pen. Real tree. % DIFF. Img Pan Imag Theo. % DIFF. Mag Pan. Mag Theo. % DIFF. Phase Pn.			(plunge .01 h/2	b, .37c, N/	ACA 0007.	100 penels, 3	cyc66)						
Real theo. % Diff. Imag Pan Imag Theo. % Diff. Mag Pan. Mag Pan. Mag Theo. % Diff. Phase Pn. 0.00016 0.000168366 1.03% 0.00081 0.00080678 0.000826 0.000826 0.000822 0.000822 0.000822 0.000826 0.000826 0.000822 0.000826 0.00082 0.000826 0.0008			Kpenel (equal t	3 2 x Theol	rdonen Kt)		SOIFF tel	ten wrt Theos	donen veku	į			
Real pen. Real theo. % Diff. Imag Theo. % Diff. Mag Pen. Mag Pen. Mag Theo. % Diff. Phree Pn. 0,00016 0,00016 0,00016 0,00016 0,000246778 0,000127 0,000162 0,00062 0,42% 78.82186 0,000031 0,000246778 86.83% 0,000126 0,0001283 0,001612 0,00162 0,00162 0,00162 0,00163<													
0.00016 0.00016 <t< th=""><th>Ē</th><th>Real pen.</th><th>Real theo.</th><th>Γ.</th><th>П</th><th>Imag Theo.</th><th>% DIFF.</th><th>Mag Pan.</th><th>Mag Theo.</th><th>% DIFF.</th><th>Phese Pn.</th><th>F</th><th>- L</th></t<>	Ē	Real pen.	Real theo.	Γ.	П	Imag Theo.	% DIFF.	Mag Pan.	Mag Theo.	% DIFF.	Phese Pn.	F	- L
0.00016 0.000168366 1.03% 0.00081 0.0008078 0.40% 0.000826 0.000822 0.42% 78.828162 70.0001 0.000246778 86.83% 0.00010 0.00128462 0.37% 0.001283 0.001067 88.87% 46.7% 78.211322 70.00024 0.00034 0.00034 0.0012864 0.001284 0.001284 0.001284 73.482188 73.482188 0.00063 0.00088658 7.32% 0.00184048 0.057% 0.00134 0.000374 0.00047 0.000474 0.00047 0.000474 0.00047 0.000474 0.000474 0.000474 0.000474 0.000474 0.000474 0.000474 0.000474 0.000374 0.000774 0.000474 0.000774 0.000474 0.000774 0.000774 0.000774 0.000774 0.000774 0.000774 0.000774 0.000774 0.000774 0.000774 0.000774 0.000774 0.000774 0.000774 0.000774 0.000774 0.000774 0.0000774 0.000774 0.000774 0.000774 0.000774 0.000774 0.000774 0.00					T								
0.000011 0.0002467781 96.83% 0.000011 0.0002467781 96.83% 0.001031 0.0002467781 96.83% 0.001031 0.0002467781 96.83% 0.00126422 0.37% 1.41E-06 0.001024 0.0013 0.67% 75.211322 7<	11998	L	1	1.03%	0.00081	0.00060678	0.40%	0.000826		0.42%	78.826162	78.90	0.00
0.00043 0.0003416041 3.37% 0.00126 0.00126462 0.37% 0.001283 0.001283 0.001467 0.00146788 0.65% 0.001624 0.00146788 0.65% 0.001624 0.00146788 0.65% 0.001624 0.001624 0.00146788 0.65% 0.001624 0.001624 0.00146788 0.65% 0.001624 0.001624 0.001626 0.001624 0.001624 0.001624 0.001624 0.001624 0.001624 0.001626 0.00162	0 18	_		96.93%	0.00001	0.00103796	89.04%	L		98.97%	46		41.31%
0.00043 0.0004436581 3.06% 0.00146 0.0014578 0.001612 0.001624 0.076% 73.462166 73.46216 73.46216 73.46216 73.462166 </td <td>200</td> <td>1</td> <td>1</td> <td>3.37%</td> <td>0.00126</td> <td>0.00126462</td> <td>0.37%</td> <td>0.001283</td> <td>0.0013</td> <td></td> <td></td> <td></td> <td>0.69%</td>	200	1	1	3.37%	0.00126	0.00126462	0.37%	0.001283	0.0013				0.69%
0.00063 0.000661735 4.80% 0.00183 0.00184043 0.67% 0.001836 0.001840 71.003346 71.003346 71.003346 71.003346 71.003346 71.003346 71.003346 71.003346 71.003346 71.003346 71.003346 71.003346 71.003346 71.003346 71.003346 71.0034 71.0034 71.0034 71.0034 71.0034 71.00346 71.00344 71.00344<	0 24	1	-1-	3.00%	0.00146	0.00145798		١.	ō		73.482186	73.08	0.66%
0.00063 0.0006853 7.32% 0.00218 0.00218438 1.67% 0.002314 0.00237 2.37% 66.980266 0.00104 0.0011445091 8.13% 0.00249 0.0026241 1.56% 0.002833 0.002776 2.80% 67.331136 6 0.00137 0.00137 0.002686 0.00273653 1.66% 0.002833 0.003037 3.41% 96.483646 6 0.00137 0.00164 0.00266 0.002378 0.002833 0.00392 3.41% 96.483646 6 0.00161 0.00163601 12.26% 0.002372 0.003246 0.00378 3.67% 96.193616 6 0.00161 0.00162601 13.26% 0.00372 0.003646 0.003646 0.00346 0.00378 3.67% 96.185116 96.185116 0.0016261 0.002301 13.26% 0.00372 0.00373 0.003681 0.004216 0.00373 3.41% 96.185116 96.18651 96.18651 96.18661 96.00441 96.00441 96.18661	0 32	1		4.80%	0.00183	0.00184043	L	L	<u> 1 —</u>		_	70.22	1.11%
0.00104 0.0011445091 8.13% 0.00249 0.00262841 1.56% 0.002636 0.00268 0.00268 0.00268 0.00268 0.00268 0.00268 0.00268 0.00268 0.002736 0.00268 0.00268 0.002736 0.00268 0.00268 0.002736 0.00268 0.00268 0.002736 0.00268 0.002736 0.00273 0.00268 0.00273 0.00273 0.00274 0.00274 0.00274 0.00274 0.00276	40	1	1_	7.32%	0.00218	0.00219439	1.67%	Ļ.	J	2.37%		87.8	1.74%
0.001171 0.0013199961 11.30% 0.00269 0.00273653 1.86% 0.002832 0.003037 3.41% 96.4936449 0.001171 0.001546041 11.30% 0.00289 0.00300637 1.61% 0.003262 0.003382 3.57% 96.163516 0.00161 0.001546041 11.26% 0.00289 0.00300637 1.61% 0.003245 0.00378 3.84% 93.786452 9 0.00161 0.001376269 13.50% 0.00372 0.00376861 1.37% 0.004218 0.00417 4.61% 91.83111 5 0.00417 0.00417 4.61% 91.8 91.83111 5 0.00353 0.004187216 16.70% 0.0052 0.0052383 0.73% 0.006284 0.006264 0.0062706 0.006270 0.006270 0.006284 5 0.006270 0.00417 7.82% 0.006684 7 0.001207 0.01334846 18.05% 0.00681 0.006687 0.0188 0.026 0.01847 0.13683 12.26% 27.6416 0.02372 17.84 0.03528 13.2468 13.2468 13.2468 13.2468 13.2468 13.34688 13.34688 13.34688 13.34688 13.34688 13.34688 1	0.48	1	4-	9.13%	1	0.00262941	1.50%	L				_	2.66%
0.00137/ 0.001646041 11.38% 0.00266 0.0036262 0.00362 3.57% 66.163616 0.00161 0.00185016 12.26% 0.00372 0.0031671 1.41% 0.003645 0.00378 3.84% 63.786452 96.163616 0.00161 0.00185016 13.26% 0.00372 0.00376861 1.37% 0.004218 0.004417 4.61% 91.83111 61.83711 61.8371 62.77642	0.63	1	.1.	11.30%		0.00273663		l_	0.003037				3.48%
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0.01334946 16.05% 0.00861 0.00869028 0.25% 0.014769 0.016437 10.17% 40.62587 3 10.034412725 14.78% 0.01536 0.015487 0.71% 0.033104 0.03773 12.26% 27.6416 0.1335246 13.04% 0.02734 0.0303886 10.02% 0.119447 0.136963 12.86% 13.34968 1	1.0	0.005553	1_	١_		0.00668476			0.009417			- 1	28.
0.034412726 14.78% 0.01636 0.015487 0.71% 0.033104 0.03773 12.26% 27.6416	2.4	0.011207	1_	ì		0.00969028	_	L	0.016437	Ì	40.62597	_	13.82%
0.13553400 13.04% 0.02734 0.0303886 10.02% 0.118447 0.136963 12.88% 13.34898	4	0.029326	12	1	0.01536			L.			27.6416		14.20%
0.1104.0 C.136.0 C.136	8	11 0.115247	0.132523409	13.04%	0.02734	0.0303886	10.02%	0.118447	0.136963	12.86%	13.34668	_ 1	3.34%

TABLE 2.8 PLUNGE h/2b=.01 C_M COMPARISON

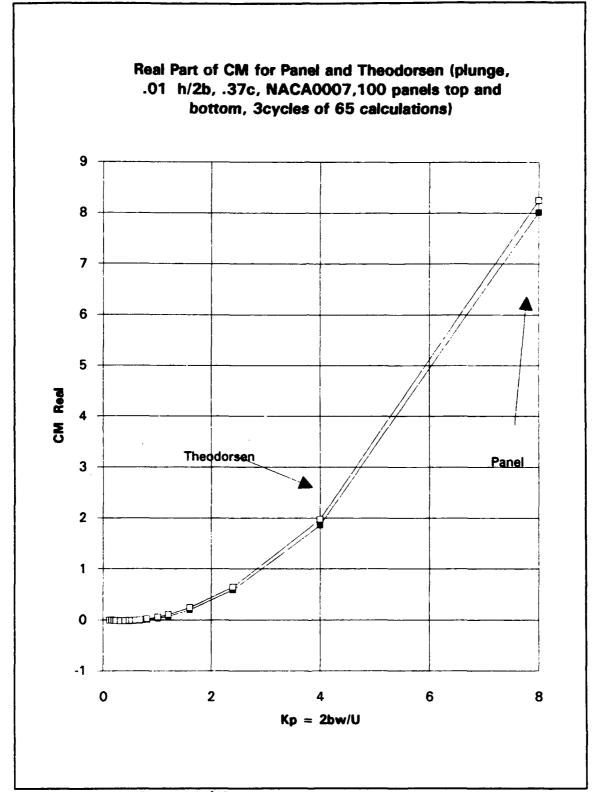


Figure 2.53 Plunge h/2b=.01 C_M Re

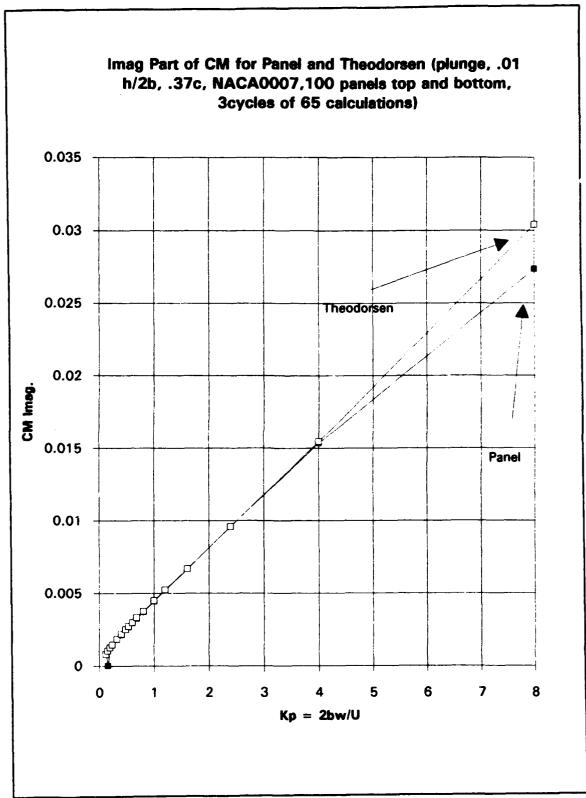


Figure 2.54 Plunge h/2b=.01 C_M Im

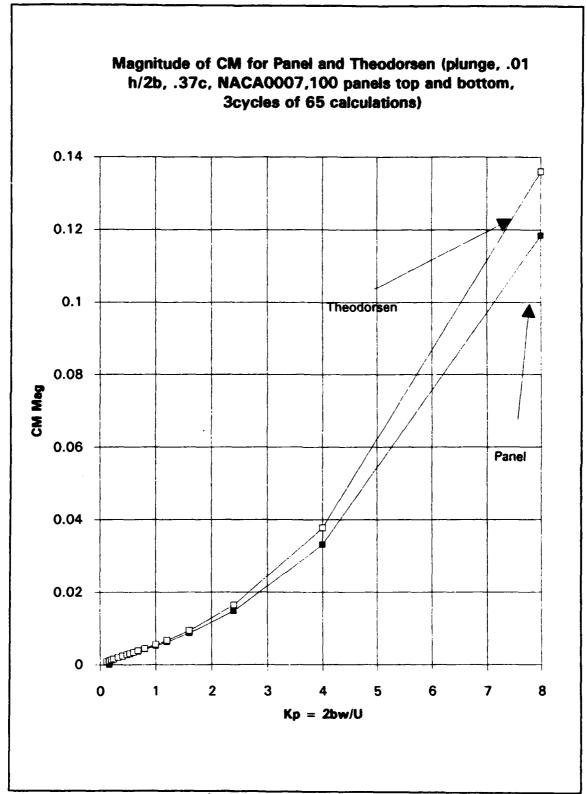


Figure 2.55 Plunge h/2b=.01 C_M Magnitude

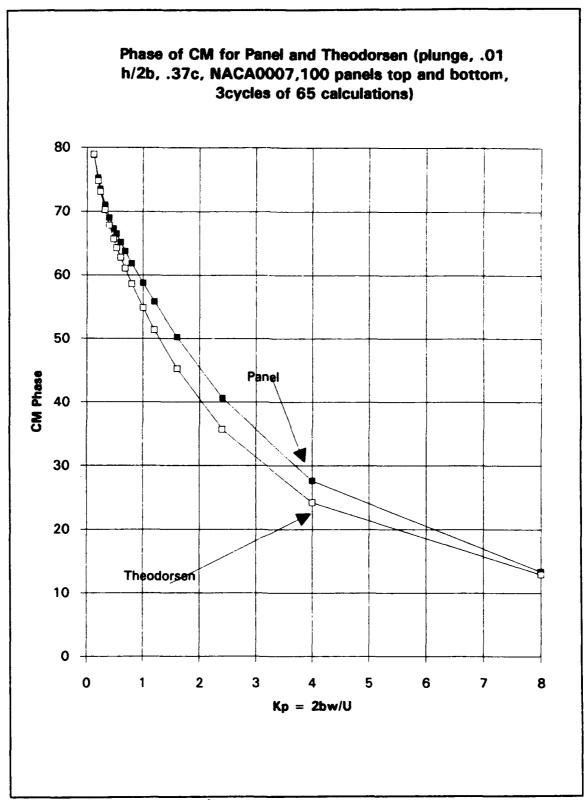


Figure 2.56 Plunge h/2b=.01 C_M Phase

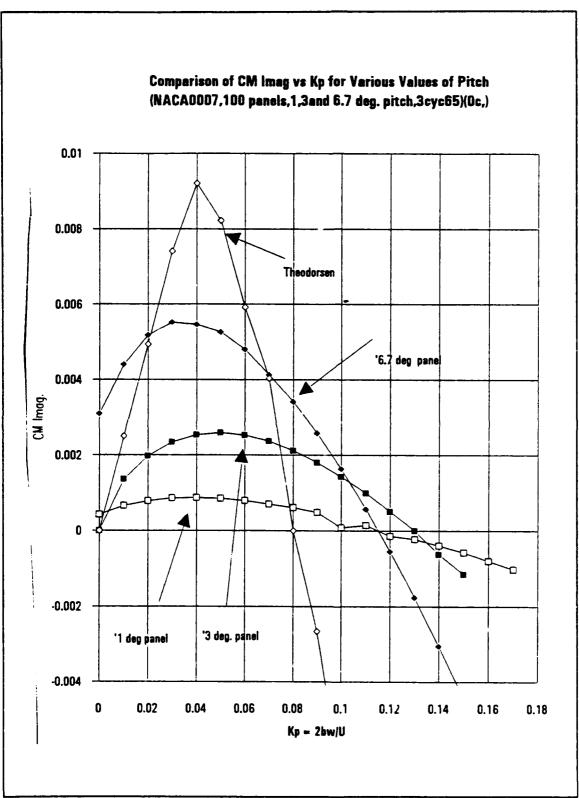


Figure 2.57 Pitch Oc. 1.0,3.0, and 6.7 degrees vs Theodorsen

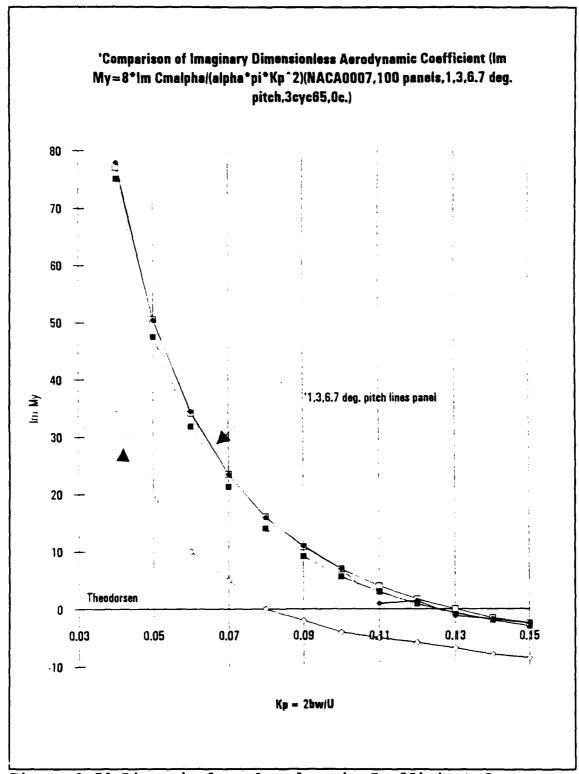


Figure 2.58 Dimensionless Aerodynamic Coefficient for 1.0,3.0, and 6.7 degrees

III. FLUTTER DETERMINANT

The proven accuracy of the UPOT Code enabled it to be used for the solution of the flutter determinant.

A. FLUTTER THEORY

In order to analyze the phenomenon of flutter, it is necessary to obtain the equations of motion of the system. To simplify the problem the assumption is made that the actual motion of the system can be considered a combination of fundamental wing bending, and fundamental wing torsion. The system can then be replaced by an equivalent system containing an airfoil section of unit span restrained by springs against independent vertical motion (bending), and torsion as illustrated in Figure 3.1. This paper will not consider the aileron hinge case so ß and c are set equal to zero. According to the class notes of M. Platzer [ref.1] the formulation proceeds as follows:

Consider the balance of the elastic, inertial and aerodynamic forces on a mass element:

- Total Inertial force: -/dm(h"+rα") = -(Mh"+S_αα")
 Mass: M=/dm
 Static Moment about the elastic axis: S_α = /rdm
- The moments about the elastic axis are:

$$-\int r (h'' + r\alpha'') dm = -(I_{\alpha}\alpha'' + S_{\alpha}h'')$$
 (3.1)

Mass moment of inertia about elastic axis

$$I_{\alpha} = \int r^2 dm$$

• Elastic restoring forces are: $-hC_h$ $-\alpha C_\alpha$ The Equations of motion therefore become:

$$h''M+\alpha''S_{\alpha}+hC_{h} = L$$

$$\alpha''I_{n}+h''S_{n}+\alpha C_{n} = M$$
(3.2)

Where: C_{α} = Torsional stiffness of the wing

 C_h = Stiffness of the wing in translation (plunge)

M = Mass of the wing per unit span

These equations can be written in a different way by expressing the spring constants in terms of the natural frequencies. Consider the airfoil to be so restrained that only one degree of freedom is permitted. The equations of motion become:

$$Mh''+hC_h=0 \quad \text{so that} \quad \omega_h=\sqrt{\frac{C_h}{M}}$$

$$I_\alpha\alpha''I_\alpha+\alpha C_\alpha=0 \quad \text{so that} \quad \omega_h=\sqrt{\frac{C_\alpha}{I_\alpha}}$$

Hence: $C_h = M\omega_h^2$ $C_{\alpha} = I_{\alpha}\omega_{\alpha}^2$

The small structural damping of metal aircraft may be approximated by a force that opposes the motion and is in phase with the velocity. One assumes therefore that the

magnitude of the damping is proportional to the elastic restoring force. Since the motion of the airfoil is harmonic at the critical flutter condition, the structural damping can be accounted for by replacing the terms:

$$hC_h$$
 with $hC_h(1+ig_h)$

$$\alpha C_a$$
 with $\alpha C_a (1+ig_a)$

Where g_h and g_α are damping constants multiplied by i to ensure that the damping force is in phase with the velocities in the simple harmonic motion.

From equation 3.3 with:

$$h(t) = he^{iet}$$
 and $\alpha(t) = \alpha e^{iet}$

We have:

$$h'' = \omega^2 h e^{i\omega t}$$
 and $\alpha'' = -\omega^2 \alpha e^{i\omega t}$

And the equations of motion become:

$$e^{i\omega t} \left(-\omega^2 h M - \omega^2 \alpha S_a + h C_h\right) = L \tag{3.4}$$

$$e^{i\omega t} \left(-\omega^2 \alpha I_{\alpha} - \omega^2 h S_{\alpha} + \alpha C_{\alpha} \right) = M \tag{3.5}$$

The equations for the aerodynamic forces were given by Fung [ref.5] and are shown here:

$$L = \pi \rho b^3 \omega^2 \left(L_h \frac{h}{b} + \left[L_\alpha - \left(\frac{1}{2} + a \right) L_h \right] \alpha \right) e^{i\omega t}$$
 (3.6)

Equating equation 3.4 to 3.6 and 3.5 to 3.7 yields:

Substituting into equation 3.8 and 3.9 for C_h and C_α and using the following dimensional terms:

$$M = \pi \rho b^{4} \omega^{2} \left(\left[M_{h} - \left(\frac{1}{2} + a \right) L_{h} \right] \frac{h}{b} + \left[M_{\alpha} - \left(\frac{1}{2} + a \right) \left(L_{\alpha} + M_{h} \right) + \left(\frac{1}{2} + a \right)^{2} L_{h} \right] \alpha \right) e^{i\omega t}$$
(3.7)

$$(-\omega^2 Mh - \omega^2 \alpha S_a + hC_h) = \pi \rho b^3 \omega^2 (L_h \frac{h}{b} + [L_a - (\frac{1}{2} + a) L_h] \alpha)$$
 (3.8)

$$(-\omega^{2}\alpha I_{\alpha} - \omega^{2}hS_{\alpha} + \alpha C_{\alpha}) = \pi \rho b^{4}\omega^{2} ([M_{h} - (\frac{1}{2} + a) L_{h}] \frac{h}{b} + [M_{\alpha} - (\frac{1}{2} + a) (L_{\alpha} + M_{h}) + (\frac{1}{2} + a)^{2}L_{h}] \alpha)$$
(3.9)

$$\mu = \frac{M}{\pi \rho b^2} \qquad x_{\alpha} = \frac{S_{\alpha}}{Mb} \qquad r_{\alpha} = \sqrt{\frac{I_{\alpha}}{Mb^2}} \qquad (3.10)$$

The equations simplify and after bringing all terms to the left result in:

$$A\frac{h}{b} + B\alpha = 0$$

$$D\frac{h}{b} + E\alpha = 0$$
(3.11)

This is a homogeneous equation whose solution is obtained if the flutter determinant is zero.

$$\begin{bmatrix} A & B \\ D & E \end{bmatrix} = 0 \tag{3.12}$$

Where:

$$A = \mu \left[1 - \left(\frac{\omega_{\alpha}}{\omega}\right)^{2} \left(\frac{\omega h}{\omega_{\alpha}}\right)^{2} (1 + ig_{h})\right] + L_{h}$$

$$B = \mu X_{\alpha} + L_{\alpha} - L_{h} (\sqrt{2} + a)$$

$$D = \mu X_{\alpha} + \sqrt{2} - L_{h} (\sqrt{2} + a)$$

$$E = \mu T_{\alpha}^{2} \left[1 - \left(\frac{\omega_{\alpha}}{\omega}\right)^{2} (1 + ig_{\alpha})\right] - \sqrt{2} (\sqrt{2} + a) + M_{\alpha} - L_{\alpha} (\sqrt{2} + a) + L_{h} (\sqrt{2} + a)^{2}$$
(3.13)

 μ is the ratio of the mass of the wing to the mass of a cylinder of air of a diameter equal to the chord of the wing. ω_{α} and ω_{h} are the natural angular frequency (rad/sec) of torsional vibration around "a" (elastic axis) and the natural frequency in deflection, respectively. x_{α} is the location of center of gravity of the wing measured from a. ω is the circular frequency of wing vibration.

The relationships between the code and Theodorsen derived earlier in Chapter II can be used here to simplify the equations: (note: no damping in this case $g_a = g_b = 0$)

For A: manipulating equation 2.20,

$$L_{h} = \frac{2C_{Lh}}{\pi K_{p}^{2} \left(\frac{h}{2b}\right)}$$
 (3.14)

resulting in:

$$A=\mu \left[1-\left(\frac{\omega_{\alpha}}{\omega}\right)^{2}\left(\frac{\omega h}{\omega_{\alpha}}\right)^{2}\right]+\frac{2C_{L\alpha}}{\pi K_{p}^{2}\left(\frac{h}{2h}\right)}$$
(3.15)

For B: manipulating equation 2.14,

$$L_{\alpha} - L_{h} (1/2 + a) = \frac{4 C_{L\alpha}}{\pi K_{p}^{2} \alpha}$$
 (3.16)

resulting in:

$$B = \mu X_{\alpha} + \frac{4C_{L\alpha}}{\pi K_{D}^{2}\alpha}$$
 (3.17)

For D: manipulating equation 2.28

$$L_{\alpha} - L_{h} (1/2 + a) = \frac{4 C_{Mh}}{\pi K_{p}^{2} (\frac{h}{2b})}$$
 (3.18)

resulting in:

$$D = \mu x_{\alpha} + \frac{4C_{Mh}}{\pi K_{p}^{2} \left(\frac{h}{2b}\right)}$$
 (3.19)

For E: manipulating equation 2.24

$$-\frac{1}{2}(\frac{1}{2}+a) + M_{\alpha} - L_{\alpha}(\frac{1}{2}+a) + L_{h}(\frac{1}{2}+a)^{2} = \frac{8C_{M\alpha}}{\alpha \pi K_{p}^{2}}$$
(3.20)

resulting in:

$$E = \mu r_{\alpha}^{2} \left[1 - \left(\frac{\omega_{\alpha}}{\omega} \right)^{2} \right] + \frac{8 C_{M\alpha}}{\alpha \pi K_{D}^{2}}$$
 (3.21)

The determinant is expanded to AE-BD=0, and the real and imaginary parts are set equal to zero. Substituting $(\omega_{\alpha}/\omega)^2$ = X and solving the real (2 roots) and imaginary (1 root) equations for values of X corresponding to each reduced frequency value. These X values can be plotted as SQRT(X)

against K_p and any intersections of real and imaginary parts signify a flutter point.

Knowing that:

$$K_p = \frac{2b\omega}{U}$$
 and $\sqrt{X} = (\frac{\omega_a}{\omega})$ (3.22)

solve for Ucritical

$$U_{critical} = \frac{2b\omega_{\alpha}}{K_{p}\sqrt{X}}$$
 (3.23)

which is the critical flutter speed.

B. UPOTFLUT CODE

1. FORMULATION AND INPUT

The equations derived in the flutter theory section above were programmed into a FORTRAN subroutine and attached to the UPOT.f code. The UPOT code was modified first to enable it to conduct a frequency sweep of pitch and plunge simultaneously. The resulting frequency sweep pitch and plunge array data is then sent to the flutter subroutine which provides the values of SQRT(x) and K_p for plotting. The program also gives a best guess for the $U_{critical}$ based on the difference betweeen the real and imaginary SQRT (X) values. The input file UPOTFLUT.IN is very similar to the regular UPOT.IN file with the addition of actual physical properties of the system being analyzed. The user should start the

analysis in the pitch mode first (IOSCIL =1, ITRANS =0) to ensure complete coverage of all frequencies of interest. The following relations were taken from NACA TR-685 [ref.8] and should prove helpful in determining the physical properties needed for program operation.

$$\kappa = \text{mass ratio} = \pi \rho b^2 / M$$

$$\kappa = 1/\mu$$

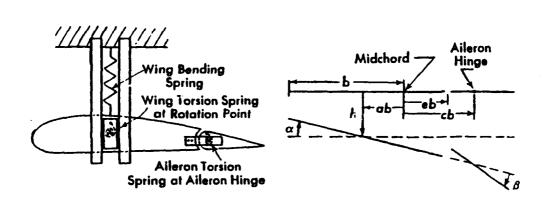
$$x_{\alpha} = S_{\alpha}/Mb$$

$$r_{\alpha}^2 = I_{\alpha}/Mb^2$$

2. OUTPUT

Outputs from the code have been limited to reduce the amount of computer space taken up by the code operation. A sample input and output file are contained in Figure 3.2. The following list describes the input/output files and the data they contain:

- a. UPOTFLUT.IN The input file figure 3.2a
- b. CL.d Same as UPOT.f output
- c. CM.d Same as UPOT.f output
- d. PHASE.d Same as UPOT.f output
- e. CPSS.d Same as UPOT.f output
- f. CPU005.d Same as UPOT.f output
- g. PHZSWP.d This file contains K_p , ϕ_L , ϕ_M , $C_{L\alpha}$, $C_{M\alpha}$
- h. PLHZSWP.d This file contains K_p , $\phi_L \phi_M$, C_{Lh} , C_{Mh}
- i. PITCH.in This file contains K_p , $C_{L\alpha}$ Re, $C_{L\alpha}$ Im, $C_{M\alpha}$ Re, $C_{M\alpha}N$ Im



b = semichord (ft.)

- cb = distance between midchord and aileron hinge, positive if aft of midchord (ft.)
- eb = distance between midchord and aileron leading edge, positive aft of midchord (ft.)
- 'ab = distance between rotation point (elastic axis) and midchord, positive if aft of midchord (ft.)
 - h = bending deflection of rotation point (elastic axis), positive downward (ft.)
- α = angular deflection about rotation point (elastic axis), positive for leading edge up (radians)
- β = angular deflection of alleron about alleron hinge relative to wing chord, positive for alleron leading edge up (radians)

Figure 3.1 Simplified System Geometry

```
. . . . . . . . .
                                                    stdin
                                                                                                        Page 1
     AIRFOIL TYPE : NACA 0012 AIRFOIL
NLOWER - 50 , NUPPER = 50
     IFLAG NLOWER NUPPER
0 50 50
ATRFOIL TYPE
              IOSCIL ALPI
1 -3.0
                                                                 PIVOT
0.3
     LIKAMP
                                             ALPMAX
                                             3.0
     FREQ
.85
                REOSTP REOFNL
     IGUST UGUST VGUST
     TTRANS DELHIX DELHY DELI PHASE
0 0.00 .0833 -.0833 0.00
CYCLE NTCYCLF TOI.
3 65 0.005
     3 65 0.005
naot 6 naot X aoa walues multiplied by 10 (integer)
2 05 10 20 25 39 50
Semi-chord Walpha Wh Mass
6 90 72.0 .53789
Talpha Salpha Density
4.84102 .645468 .002378
Comments...
JRAMP 0: n/a
1: Straight ramp
2: Modified ramp
                                        RFREQ is based on full chord
IOSCIL 0: n/a RFREQ is based on full chord
1: Sinusoidal pitch, motion starts at min Aca
ITRANS 0: n/a
1: Translational harmonic oscillation
CYCLE: # of cycles for oscillatory motions
-In case of ramp, cycle=1.5 denotes airfoil is held
at max aoa for the duration of .5 cycle
-For steady state solution set it to 0
NTCYCLE: # of time steps for each cycle CYCLE*NTCYCLE is limited to 200 currently.
NAOT: # of input aca for cp output
- angles should be in increasing order,
- for oscilatory motions angles should increase
first, then decrease. Decreasing angles are for
the return cycle..
SEMI-CHORD Half Chord in feet.
Walpha, Wh, uncoupled natural frequencies of the system in question. Walpha is pitch and Wh is plunge(HZ).
Mass
                  specific mass of the system in slugs/foot of span
Ialpha
                 Moment of Inertia of system about the elastic axis(a)
                 per unit span length.
Static moment of wing-alleron per unit span length
Salpha
Density
                 Mass of air per unit of volume(slugs per ft^3)
```

Figure 3.2a UPOTFLUT.in example input file

```
stóln Page t
      AIRFOIL TYPE : NACA 0012 AIRFOIL
NLOWER = 50 , NUPPER = 50
   OSCILLATORY MOTION, IOSCIL =
                                                                1
FREQ SWEEP
FREQ = 0.850000
                          PHASE SHIFT ANALYSIS
                          FREQ = 0.8500000
 w 0.8500000
kp= 0.8500000 ifreq
 AMRITUDE: clamp, cmamp: 0.7316691 2.9271054E-02
ioscil = 0itrans = 0
PHASE; clp, cmp: 202.4033 -63.70797
AVERAGE DRAG, TOTAL DRAG: 1.5930884E-03 0.1051438
ETAS, WBAR = 0.1430808 -1.1134184E-02
                           PHASE SHIFT ANALYSIS
                             FREQ = 0.8500000
 w 0.8500000
kp= 0.8500000 ifreq
 AMPLITUDE; clamp, cmamp : 0.2779089 2.2117507E-02 ioscil = 0itrans = 1 37.10253 AVERAGE DRAG, TOTAL DRAG : -6.2051453E-03 -0.4095396 ETAS, MBAR : 0.1050769 -0.1181067
FREQ SWEEP
FREQ = 0.860000
                          PHASE SHIFT ANALYSIS
FREQ = 0.8600000
     0.8600000
 kp= 0.8600000 ifreq
 AMPLITUDE: clamp, cmamp : 0.2317267 2.9490557E-02
poscil = clp, cmp : 202.8760 -63.85251
AVEAGE DRAG, TOTAL DRAG : 1.5921656E-03 0.1050829
ETAS, WBAR : 0.1398697 -1.1383206E-02
                         PHASE SHIFT ANALYSIS
FREQ = 0.8600000
  w 0.8600000
 kp= 0.8600000 ifreq
 AMPIITUDE; clamp, cmamp: 0.2804866 2.2494521E-02 ioscil = 0itrans = 1 1 PHASE; clp, cmp : 270.7843 36.79393 AVERAGE DRAG, TOTAL DRAG : -6.3188463E-03 -0.4170439 ETĀS, WBAR : 0.1047920 -0.1205979
FREQ SWEEP
FREQ = 0.870000
                        PHASE SHIFT ANALYSIS
FREQ = 0.8700000
 ₩ 0.8700000
```

Figure 3.2b UPOTFLUT example output file

```
stdin Pege 2
    kp= 0.8700000 ifreq
   AMPLITUDE: clamp, cmamp: 0.2317936 2.9765518E-02
loscil = 0ltrans = 0
PHASE; clp, cmp : 203.3604 -64.02047
AVERAGE DRAG, TOTAL DRAG : 1.5893428E-03 0.1048966
ETAS, WBAR : -0.1365460 -1.1639614E-03
                                                                           -1.1639614E-02
                               PHASE SHIFT ANALYSIS
FREQ = 0.8700000
    w 0.8700000
    kp= 0.8700000 ifreq
   AMPLITUDE: clamp, cmamp: 0.2830637 2.2874046E-02
ioscil = 0itrans = 1
PHASE: clp, cmp: 271.0655 36.47753
AVERAGE DRAG, TOTAL DRAG: -6.4334869E-03 -0.4246101
ETAS, MBAR: 0.1045149 -0.1231114
  FREQ SWEEP
FREQ = 0.880000
                              PHASE SHIFT ANALYSIS
FREQ = 0.8800000
    w 0.8800000
kp= 0.8800000 ifreq
   AMPLITUDE: clamp, cmamp: 0.2318744 3.0037180E-02
ioscil = 0itrans = 0
PHASE; clp, cmp : 203.8330 -64,15525
AVERAGE DRAG, TOTAL DRAG : 1.5880425E-03 0.1048108
ETAS, WBAR : -0.1335113 -1.1894441E-02
    ETAS, WBAR
                              PHASE SHIFT ANALYSIS
FREQ = 0.8800000
    ₩ 0.8800000
    kp= 0.8800000 ifreq
    AMPLITUDE; clamp, cmamp: 0.2856959 2.3258235E-02
joscil = 0itrans = 1
PHASE; clp, cmp: 271.3546 36.17284
AVERAGE DRAG, TOTAL DRAG: -6.5488103E-03 -0.4322215
ETAS, NBAR: 0.1042214 -0.1256711
  FREQ SNEEP
FREQ - 0.890000
                              PHASE SHIFT ANALYSIS
FREQ = 0.8900000
    ₩ 0.8900000
    kp= 0.8900000 ifreq
    AMPLITUDE: clamp, cmamp: 0.2319494 3.0311935E
ioscil = 0itrans = 0
PHASC; clp, cmp: 204.3115 -64.29196
AVERAGE DRAG, TOTAL DRAG: 1.5859993E-03 0.1046759
ETAS, MBAR : -0.1304959 -1.21536379
                                                                            3.0311935E-02
                                                                             -1.2153637E-02
       PHASE SHIFT ANALYSIS

0.8900000

D= 0.800000
    kp= 0.8900000 1freq
    AMPLITUDE: clamp, cmamp: 0.2883391
                                                                          2.3644408E-02
```

Figure 3.2c UPOTFLUT example output file

```
stdin Page 3
 ioscil = Oitrans = 1
PHASE; clp, cmp : 271.6436 35.87401
AVERAGE DRAG, TOTAL DRAG : -6.6649993E-03 -0.4398900
ETAS, WBAR : 0.1039310 -0.1282581
FREQ SWEEP
FREQ = 0.900000
                           PHASE SHIFT ANALYSIS
FREQ = 0.9000000
  w 0.9000000
 kp= 0.9000000 lfreq
 PHASE SHIFT ANALYSIS
FREQ = 0.9000000
 w 0.9000000
kp= 0.9000000 lfreq
 AMPLITUDE; clamp, cmamp : 0.2909827 2.4039967E-02 ioscil = 0itrans = 1 1 PHASE; clp, cmp : 271.9288 35.58691 AVERAGE DRAG, TOTAL DRAG : -6.7821071E-03 -0.4476191 ETAS, WBAR : 0.1036481 -0.1308680
FREQ SWEEP
FREQ = 0.910000
                          PHASE SHIFT ANALYSIS
FREQ = 0.9100000
     0.9100000
  kp= 0.9100000 ifreq
 AMPLITUDE: clamp, cmamp: 0.2321466 3.0865142E-02
10scil = 0itrans = 0
PHASE: cip, cmp : 205.2529 -64.61227
AVERAGE DRAG, TOTAL DRAG : 1.5800473E-03 0.1042831
ETAS, WBAR : -0.1245367 -1.2687406E-02
                                                                        -1.2687406E-02
                            PHASE SHIFT ANALYSIS
FREQ = 0.9100000
 w 0.9100000
kp= 0.9100000 ifreq
 AMPLITUDE: clamp, cmamp: 0.2936268 2.4440434E-02 ioscil = 01trans = 1 PHASE: clp, cmp: 272.2159 35.29980 AVERAGE DRAG, TOTAL DRAG: -6.9000078E-03 -0.4554005 ETAS, WBAR: 0.1033707 -0.1335003
FREQ SWEEP
FREQ = 0.920000
                           PHASE SHIFT ANALYSIS
FREQ = 0.9200000
 w 0.9200000
kp= 0.9200000 ifreq
```

Figure 3.2d UPOTFLUT example output file

```
FRED + 0.9700000
 AMPLITUDE: clamp, cmamp: 0.7967705 2.4843587E-02 ioscii " 01trans - 1 1 272.5011 35.01268 AVERACE DRAG, TOTAL DRAG: - 7.0186830E-03 -0.4632331 -0.1361546
FREQ SHEFF
FREQ = 0.930000
  w 0.9299999
kp= 0.9299999 Ifreq
  PMASE SHIFT AMALYSIS
FRFQ = 0.9799999
kp= 0.9799999 ifreq 9
  AMPLITUDE: clamp, cmamp : 0.7989171 2.5250317F-02 ioacil - 0ltrans - 1 34,77948 AVERAGE DRAG, TOTAL DRAG : -7.1382108E-03 -0.4711219 ETAS, MRAR : 0.1028326 -0.1388317
FRED SMEFF
FRED - 0.940000
                                  PHASE SHIFT ANALYSIS
FREQ = 0.9399999
  w 0.9399999
kp- 0.9399999 ifreq
  PRASE SHIFT ANALYSIS
FREQ = 0,9399999
  AMPLITUDE: clamp, cmamp: 0.1015640 2.5659967F-02 toactl = 0itrans = 1
    PMASE; rlp, cmp; 273,0192 34,44823
AVERAGE DRAG, TOTAL DRAG: -7.2581137F-03 -0.4790751
ETAS, MMAR : 0.1075746 -0.1415304
Mumber of Rp Values : 0.1075746 -0.1415304
Mumber of Rp Values : 10
Plunge Value/Full Chord (h/2h) = 0.0833
Alpha : 3.0000
PIVOT FOINT (a) Of Elastic Axis = -0.4000
Half Chord (b) = 4.0000
Alpha Uncoupled Nat. Freq = 90.0000
Plunge Uncoupled Nat. Freq = 90.0000
Plunge Uncoupled Nat. Freq = 77.0000
I alpha = 4.8410
S alpha = 4.8410
S alpha = 0.6455
Mass = 0.53179
Air Density = 0.53179
Air Density = 0.7000
Diff = 0.90000000
DIFF = 1.1507271F-03
SQRTX = 0.9574428
U crit = 17572.684
```

Figure 3.2e UPOTFLUT example output file

- j. PLUNGE.in This file contains $K_{\rm p},~C_{\rm Lh}$ RE, $C_{\rm Lh}$ IM, $C_{\rm mh}$ RE, $C_{\rm Mh}$ IM
- k. FLUTPLOT.d This file contains K_p , SQRT(x) Re, SQRT(X) RE, SQRT(X) IM

3. VALIDATION

The program was tested against some sample cases to check for code validity. The first case was taken from reference 6 example #1, p. 236. Figures 3.3 and 3.4 show plots of the FLUTPOT.d file. Figure 3.3 shows the initial look over a wide range of K_p and after finding the approximate flutter location Figure 3.4 shows a closer look at the K_p range of interest. This example calculated a $U_{\rm critical}$ of 161.985 ft/sec. which compares favorably to the example value of 162 ft/sec. The next example was taken from NACA TR-685 [ref.8] case #1 p. 8. Figures 3.5 and 3.6 again show the initial and final looks for this analysis. The example called for a $U_{\rm critical}$ of 567 miles/hr and the program returned a value of 570 miles/hr. Next, the code was tested over a range of ω_h/ω_α ratios as done in NACA TR-685, p11., graph I-A(a). Figure 3.7 shows the comparison between the two methods.

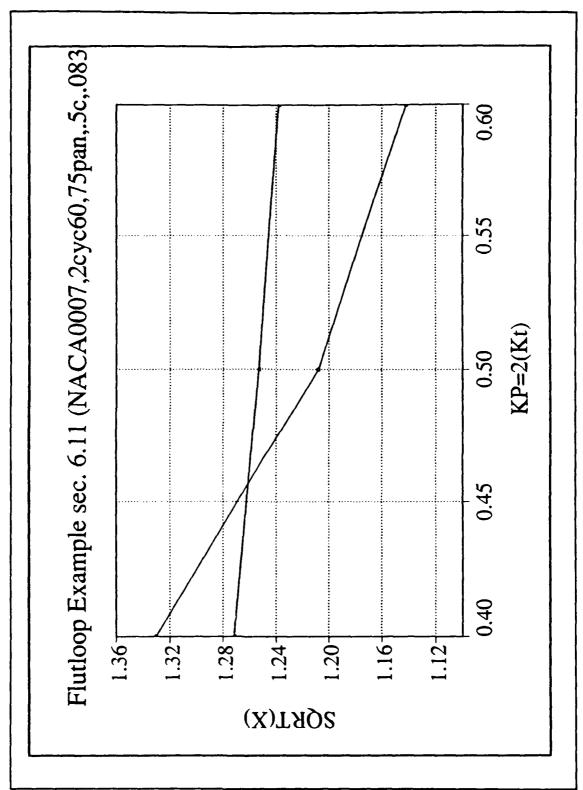


Figure 3.3 Initial look at flutter, example 1

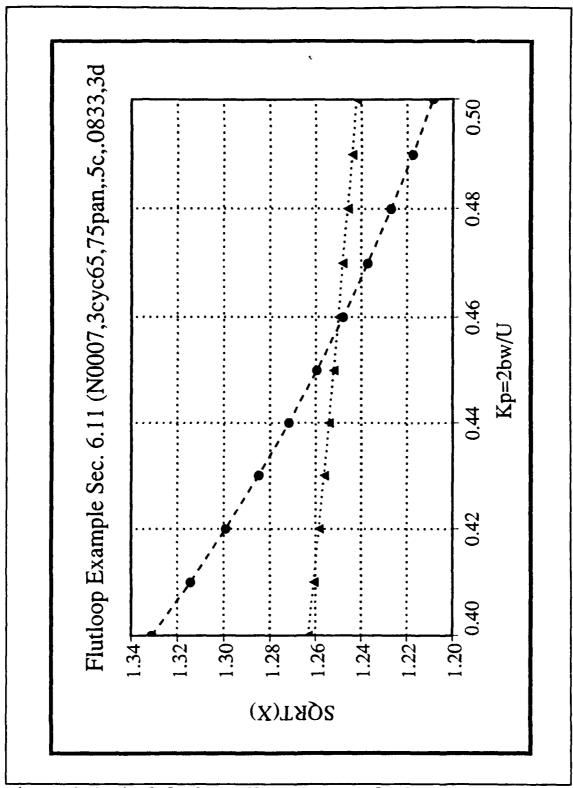


Figure 3.4 Final look at flutter, example 1

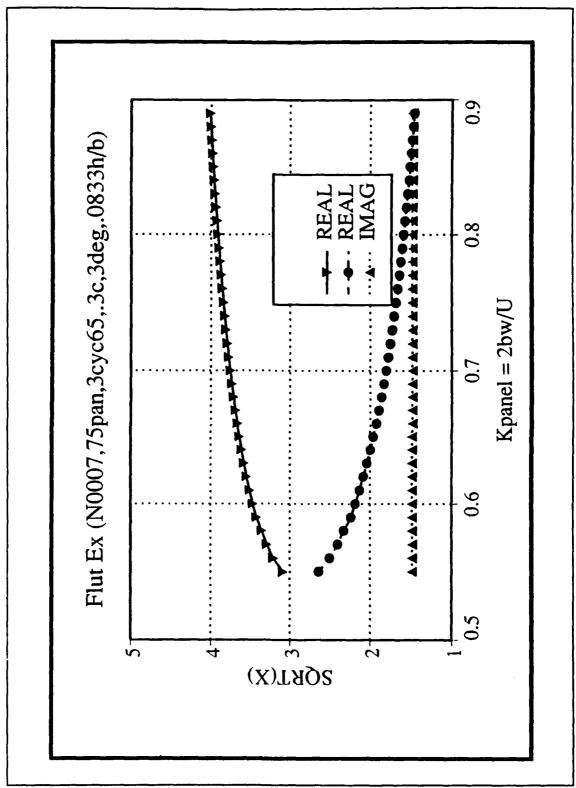


Figure 3.5 Initial look at flutter, example 2

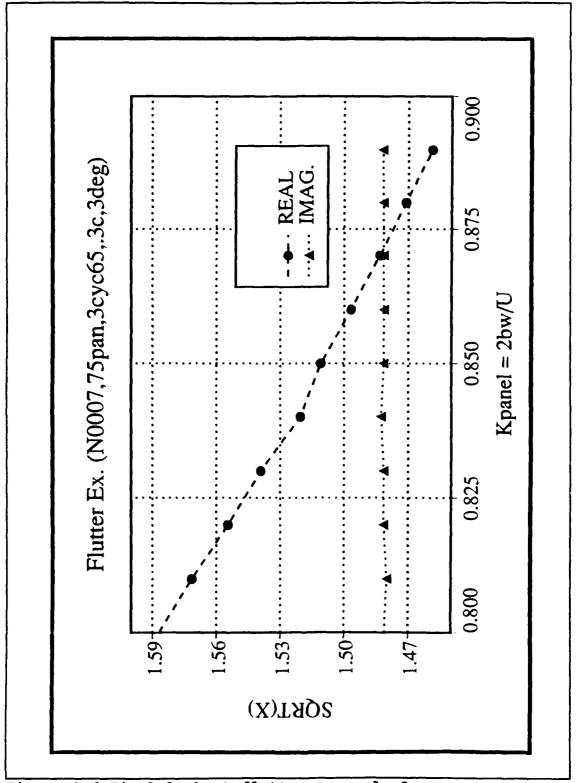


Figure 3.6 Final look at flutter, example 2

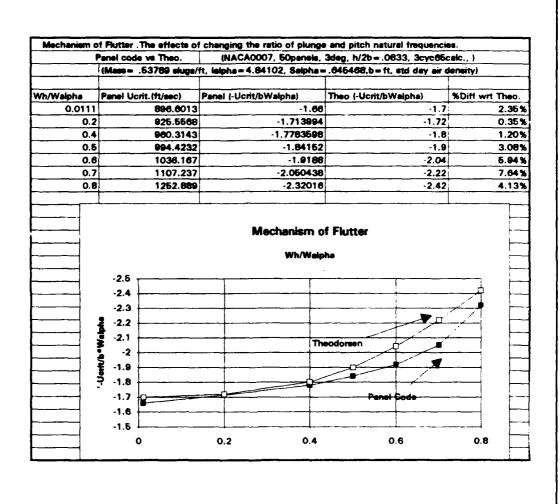


Figure 3.7 $\omega_{\rm h}/\omega_{\alpha}$ Calculations

IV. FLOW VISUALIZATION EXPERIMENT

A. INTRODUCTION

The purpose of this experiment was to document the production of thrust by a plunging airfoil. This was a preliminary experiment to better understand the vortex pattern produced by a plunging airfoil, and to examine the production of thrust using smoke flow visualization techniques.

An explanation of what constitutes a propulsive vortical signature along with smoke flow visualization of propulsive vortical patterns is given in Reference 7. In this reference, the explanation is given by contrasting the vortical pattern produced by a cylinder (drag) with the vortical pattern produced by a plunging airfoil (thrust). The cylinder produced a vortical sheet where the top row of vortices rotated clockwise and the bottom row of vortices rotated counterclockwise. This pattern induces a velocity component in the upstream direction (Biot-Savart law). contrast, the plunging airfoil produced a clockwise rotating vortex sheet on the bottom row. This pattern induces a velocity component in the downstream direction. Reproduction of the flow visualization data from Reference 7 is shown in Figure 4.1.

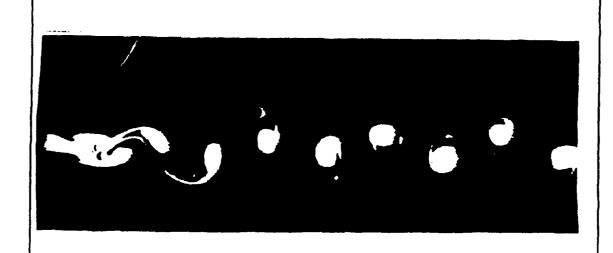




Figure 4.1 View of flow over cylinder (top) and plunging airfoil (bottom) [Ref. 7]

B. THEORY

A comparison was done using the incompressible panel code, U2DIIF. The purpose of this study was to examine the vortical pattern produced by the panel code, and determine if the vortical signature matched experimental results. The input to the panel code was set up to best match the conditions of the experiment described in the next section. The panel code was run using a plunge amplitude, h/2b equal to .1977, a reduced frequency of 1.8 and a zero mean AOA. The results of the vortical pattern are shown in Figure 4.2. Aside from the starting vortex, this is clearly a thrust producing vortical sheet. Furthermore, the vortical pattern is similar to that produced by the experiment shown in Figures 4.10 and 4.11.

C. EXPERIMENTAL SETUP

1. Plunging Airfoil

The plunging airfoil used in this paper was originally a wing taken from the rotor of a model helicopter. The wing was attached to a MB250 Shaker Table as shown in Figure 4.3 The wing was made from a NACA0007 airfoil section and consisted of a 2.45" chord and a 22" span. The wing was built from a foam core and finished with a layer of graphite epoxy composite for added fatigue strength. The airfoil's drive mechanism was a MB 250 Shaker Table capable of 1" total

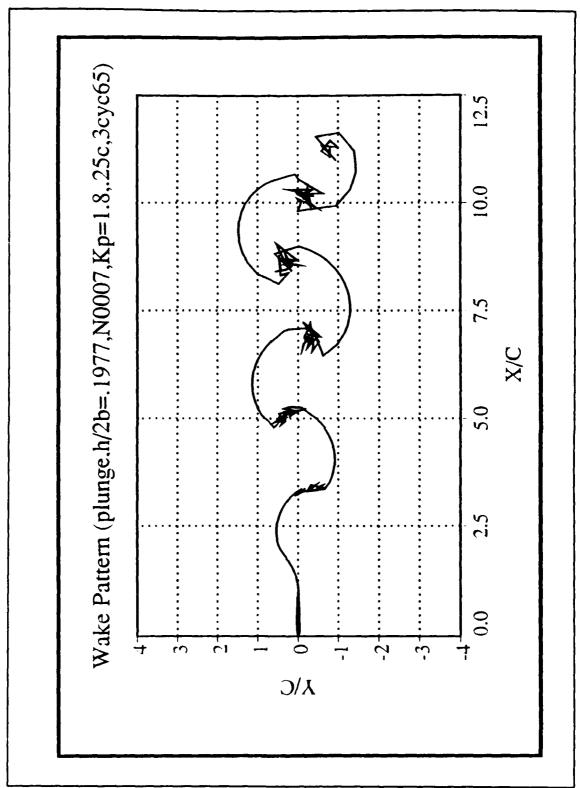


Figure 4.2 Wake pattern produced by U2DIIF code

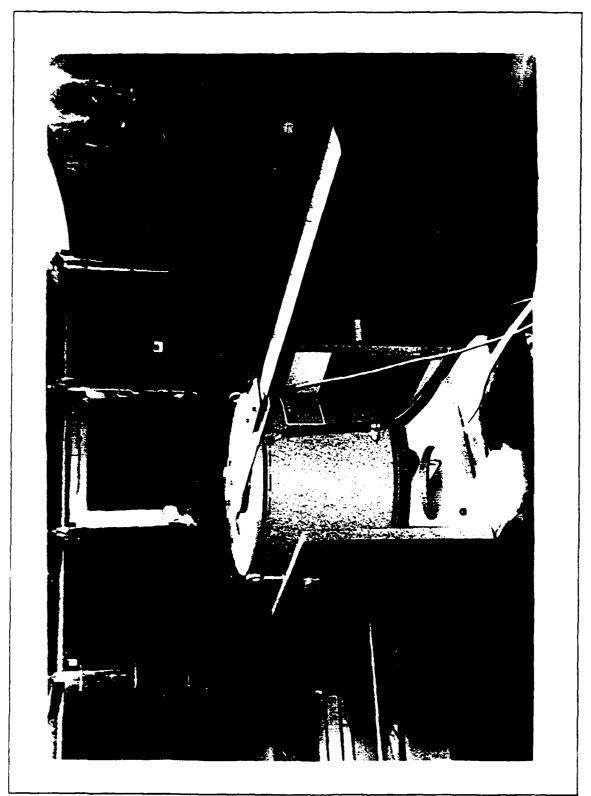


Figure 4.3 Shaker table with wing

deflection. The Shaker Table was limited only by resonance frequencies of the wing which occurred around 20 Hz or 1200 rpm.

2. WIND TUNNEL

The wind tunnel used in this experiment was a very low speed, low turbulence smoke tunnel. It is made of plexiglass walls and a contraction ratio of 2.8:1. The motor provides wind tunnel velocities between 0 and 10 feet per second (fps). The smoke was created using a Rosco smoke generator and piped into the tunnel in the test section using a small seven tube smoke rake constructed for this experiment. Figure 4.4 is a photograph of the wind tunnel and smoke rake used in this experiment.

D. TEST PROCEDURE

Testing was conducted in the low speed smoke tunnel under several different conditions. The speeds of the tunnel were approximately 1.04 fps, 1.47 fps, and 1.56 fps (measured visually). These low speeds allowed good pictures and the ability to get higher reduced frequencies without calling for too high a load on the wing. The actual plunging harmonic frequencies ranged from 1 to 15 Hz and amplitudes from 1/16" to 1" peak to peak. The tunnel was initially turned off and the Shaker Table turned on with stagnant smoke in the tunnel. The purpose was to see if the

plunging airfoil would draw the smoke through the tunnel like



Figure 4.4 Tunnel and smoke rake

a fan, thus showing the production of thrust by the plunging airfoil.

Photos were taken using a Nikon 35mm camera and Kodak TMAX-400 ASA black and white film. The shutter speed was set to 1/125 seconds with an aperture setting of 4.0 for the light conditions. Film developing time was optimized at 9 minutes at 75 degrees F.

E. RESULTS AND DISCUSSION

The result for the tunnel off condition flow visualization experiment was as expected. The wing in fact accelerated the smoke in its vicinity.

The result of the additional rake flow visualization experiments are shown in Figures 4.5-4.14. Figure 4.5 shows the stationary airfoil at zero degree AOA. The Reynolds number (based on airfoil chord) is 10,000. It can be seen that the airfoil produces a small wake with the boundary layer mostly attached. Figures 4.6 through 4.14 show the vortical wake flow patterns produced by plunge oscillations at various frequencies as indicated. Most of these pictures reveal the propulsive vortical street pattern discovered in Reference 7. Previous experiments by Neace, [ref.9] found that the tunnel was too small for the airfoil size used, but the airfoil size for the present experiment seemed to be optimum, as seen by the long trail of vortices. The vortical patterns show that the bottom vortex is rotating clockwise, and the top vortex is

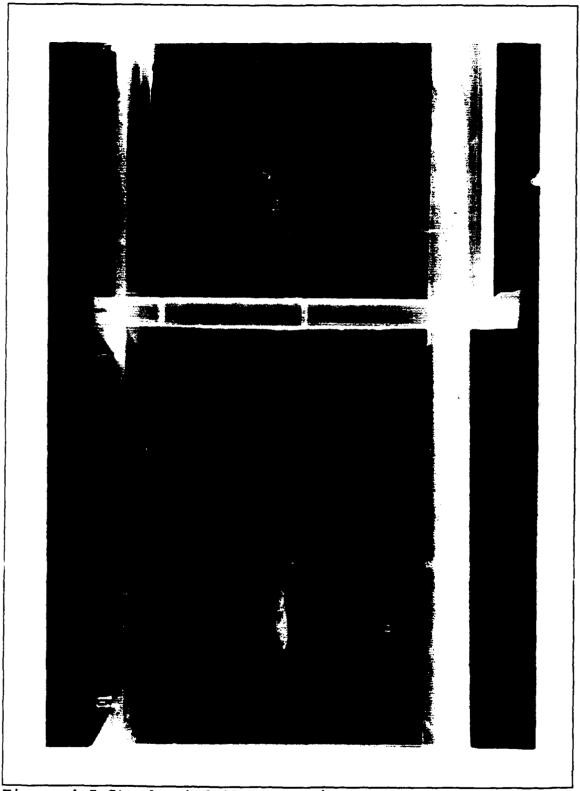


Figure 4.5 Steady airfoil 1.56 ft/s



Figure 4.6 K_p = 1.8008, h/2b=.1977, 1.56 ft/s

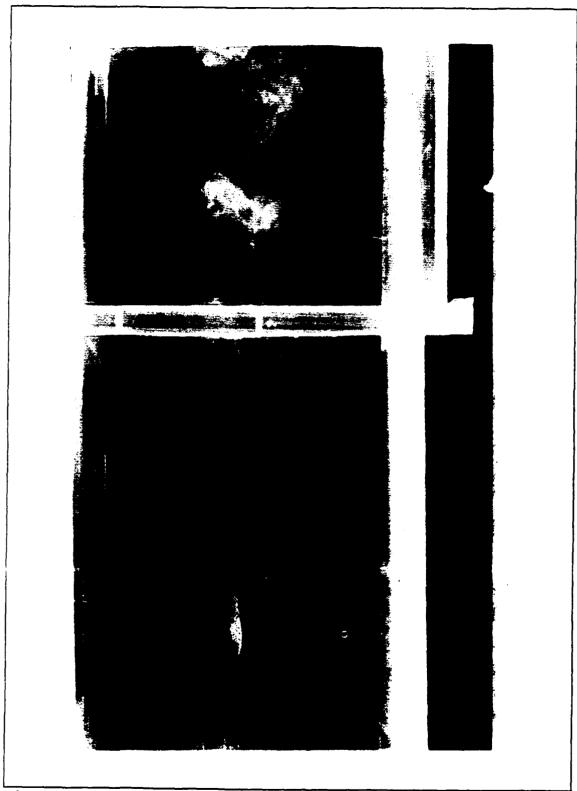


Figure 4.7 $K_p = 2.467$, h/2b=.10204, 1.56 ft/s

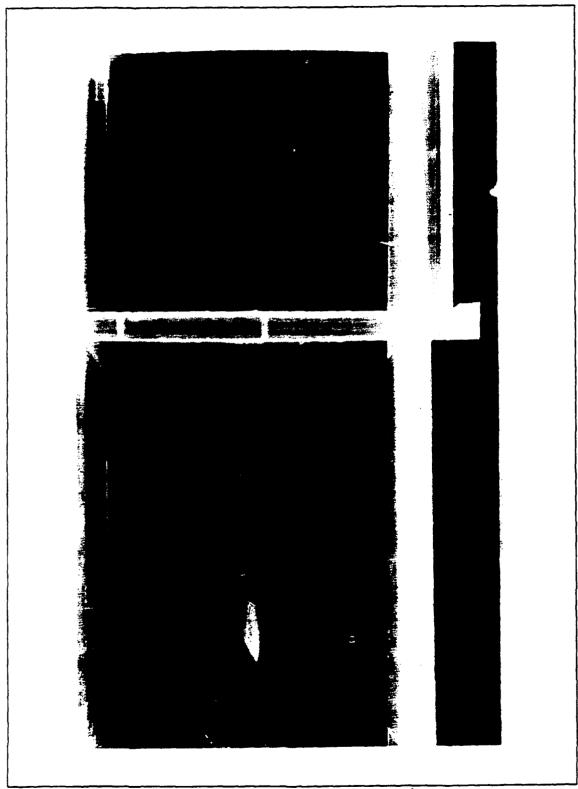


Figure 4.8 $K_p = 2.467$, h/2b=.1913, 1.56 ft/s

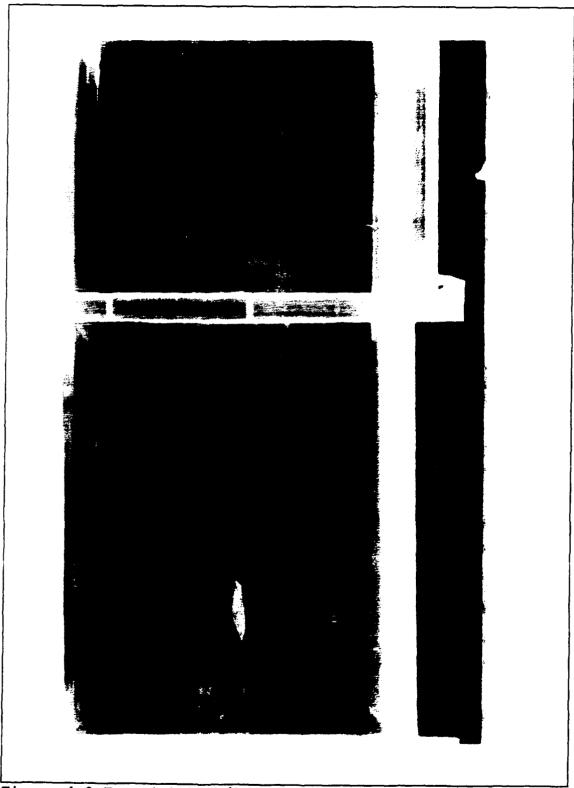


Figure 4.9 K_p = 4.112 h/2b=.14031, 1.56 ft/s

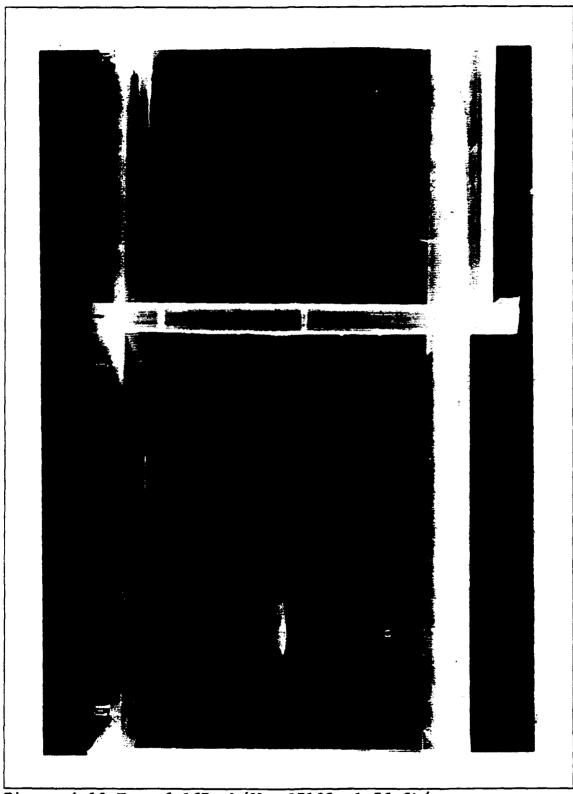


Figure 4.10 K_p = 6.167, h/2b=.05102, 1.56 ft/s



Figure 4.11 $K_p = 6.753$, h/2b=.1084, 1.56 ft/s

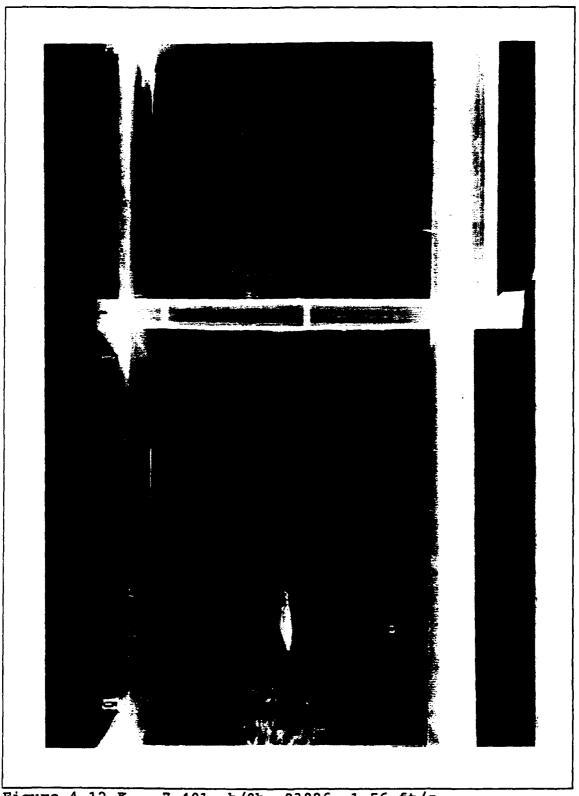


Figure 4.12 $K_p = 7.401$, h/2b=.03826, 1.56 ft/s

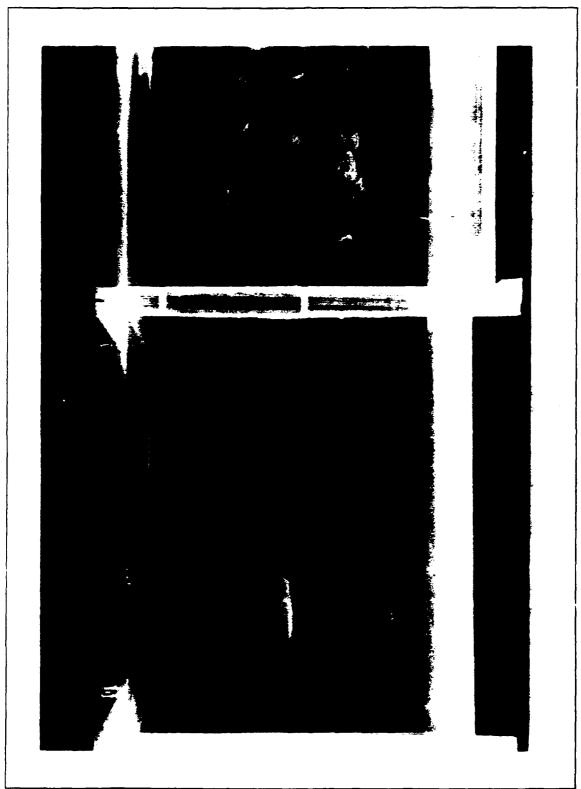


Figure 4.13 K_p =8.223, h/2b=.01913, 1.56 ft/s

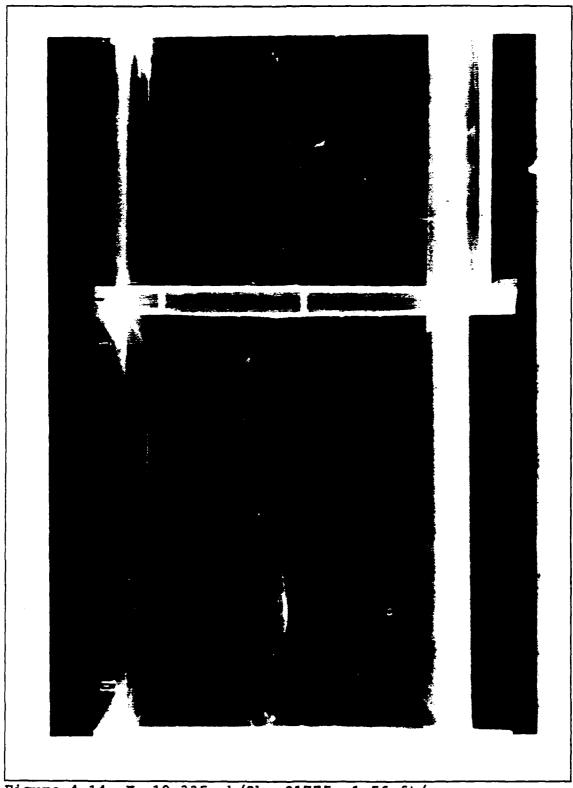


Figure 4.14, K_p=12.335, h/2b=.01775, 1.56 ft/s

rotating counterclockwise, which is a thrust producing vortical sheet. It can be seen in the pictures that the frequency greatly affects the vortical strength (size). Increasing the frequency leads to an increase in wake vorticity.

V. LIFT ENHANCEMENT PRODUCED BY A PLUNGING AIRFOIL

A. THEORY

Chapter IV demonstrated the propulsive capability of a plunging airfoil. The production of thrust implies the generation of a jet flow which, in turn, may be utilized as a boundary layer control device. Therefore, an additional test was conducted in the NPS smoke tunnel in order to explore the feasibility of this concept.

B. SETUP

The same NACA0007 plunging wing was used as in chapter IV with a different driving mechanism. The wing was mounted to an ELECTRO-SEIS Model 113 Shaker Table by APS Dynamics, Inc. The shaker was located below the test section of the NPS smoke tunnel (Figure 5.1). The plunging airfoil was mounted to struts at both ends to prevent excessive bending while plunging. The large airfoil is a cambered profile taken from the rotor of a full size helicopter (13" chord, 2" Thickness, modified NACA airfoil, Reynolds Number of 52,000). The wing is suspended from the tunnel ceiling as shown in the flow pictures. The design allowed for full movement of the big wing to position it in the vicinity of the plunging airfoil.

C. WIND TUNNEL

This study used the Naval Postgraduate School's flow visualization wind tunnel. The tunnel is an open-circuit one, with air entering an inlet that measures 4.5 m X 4.5 m (15'X15'). As the air enters the tunnel, it passes through a 7.5-cm long honeycomb. A 9:1 ratio square contraction cone directs the flow into a test section that is 1.5 m X 1.5 m (5'X5'), and 6.7 m (22') long, as seen in Figure 5.2. The flow is then exhausted into the atmosphere through a fan, which uses variable pitch blades to control the speed of the flow. The speed control toggle switch is located right below the red and green on/off switch located in the left side of the tunnel control room. The tunnel speed was determined using a digital manometer which was verified for accuracy (Figure 5.3).

An observation booth is located on the side of the tunnel. A glass window, 1.6 m X 1.1 m (5.2' X 3.4'), provides the primary viewing area from the observation room and a second one, 0.4 m X 1.23 m (1.33'X4'), is located in the tunnel's roof. The main viewing window had sufficient area for most of the photography, with the top window used for illumination. A circular turntable was located on the floor of the test section [ref.11] which allowed for easy access to the shaker table. The walls and floor of the test section were flat black for low light reflectivity.



Figure 5.1 Shaker table setup below tunnel

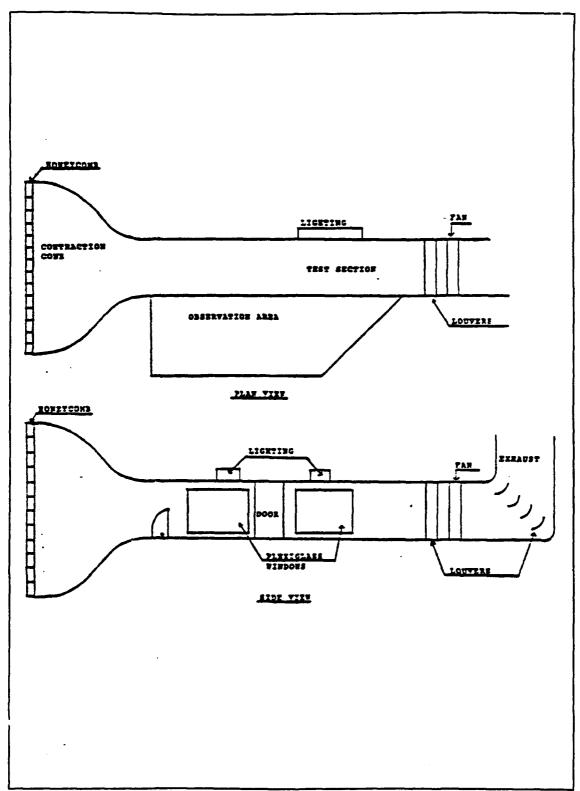


Figure 5.2 Tunnel Layout

	=		% Diff fm Acad.		5.72%	%08.0	2.96%	5.32%	4.81%	5.72%	5.53%	4.36%	4.51%	5.88%
	Comparing the digital manometer speed indications against known	Aerolab Wind Tunnel readings (3 readings taken at each value)	Aero. Vel. 9	ftls	9.845	13.9229	19.69	24.115	27.8459	31.132	34.1	39.38	44.028	53.92
Tunnel Velocity Speed Check			Dig. Vel.	tus	9.2815	14.0338	20.2735	25.397	29.1845	32.912	35.985	41.095	46.013	57.09
			Aerolab reading	, (cm H20)	20.0	0.1	0.2	0.3	0.4	0.5	9.0	0.8	1	1.5
		Aerolab Wind Tui	Digital reading	(in H20)	0.0175	0.04	0.0835	0.131	0.173	0.22	0.263	0.343	0.43	0.662

Figure 5.3 Tunnel speed check

D. SMOKE GENERATION

The smoke was generated in the Rosco smoke/fog machine. Many different smoke injection techniques were tried but with less than satisfactory results. Smoke rakes were first tried outside the tunnel with the tube number varying from 2 to 30 tubes. The tubes were inserted in the honeycomb and also separated different distances from the inlet of the tunnel. The rake was also tried inside the test section with very bad results (smoke dispersed immediately). Problems ranged from lack of smoke and turbulence when enough smoke was present. The Rosco machine at its lowest setting was producing a very high smoke volume and whenever the flow was restricted by a smoke rake the smoke production went way down. The final technique adopted was very simple. The smoke output was sent directly from the machine to a 1" nozzle which was manually waved at the entrance of the tunnel to make a steady cloud. The steady cloud was gradually pulled into the tunnel, producing a thick smoke sheet in the test section.

E. PHOTOGRAPHY

Photos were taken using a Nikon 35mm camera and Kodak TMAX-400 ASA black and white film. The film speed was set to 1/250 seconds with an aperture setting of 4.0 for the light conditions. Film developing time was optimized at 9 minutes at 75 degrees F.

F. EXPERIMENTAL PROCEDURES

The first step involved a look at the large airfoil to verify normal flow patterns (Figure 5.4 and 5.5) and find the AOA for initial trailing edge separation (Figure 5.6). Next, the plunging airfoil was placed in the tunnel by itself and a run was made to verify the propulsive capability in the larger tunnel at higher speeds. As seen in Figure 5.7, the airfoil produced a drag vortical flow. Figure 5.8 and 5.9 shows the propulsive pattern of the propulsive airfoil. Finally, the two airfoils were placed in close relative position to see the interference effect between the two airfoils.

G. RESULTS AND DISCUSSION

Several airfoil position combinations were studied, as shown in Figures 5.10 through 5.15. Figure 5.10 and 5.11 show the plunging airfoil located at approximately .65 chord of the large airfoil. Figure 5.12 through 5.15 show the plunging airfoil located at approximately .75 chord.

The differences between the plunging on and off condition were not easy to see with the eye but pictures indeed showed some differences between the two conditions. A shortcoming of this experiment was the inability of the plunging airfoil to run parallel with the large airfoil. Additionally, sizing of and relative positioning of the two airfoils was not optimized to give best results. The two airfoils were chosen from the resources available and time constraints prevented a more



Figure 5.4 Large airfoil at zero AOA

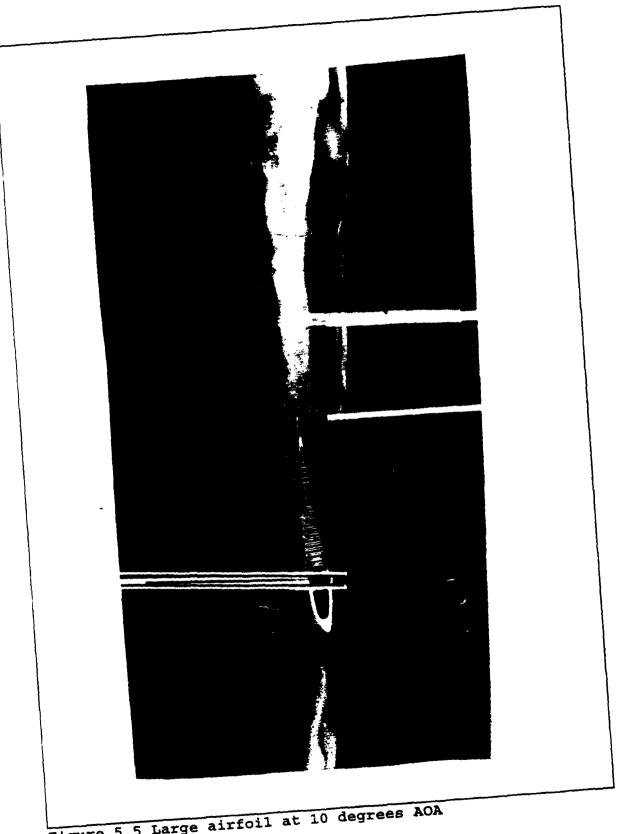


Figure 5.5 Large airfoil at 10 degrees AOA

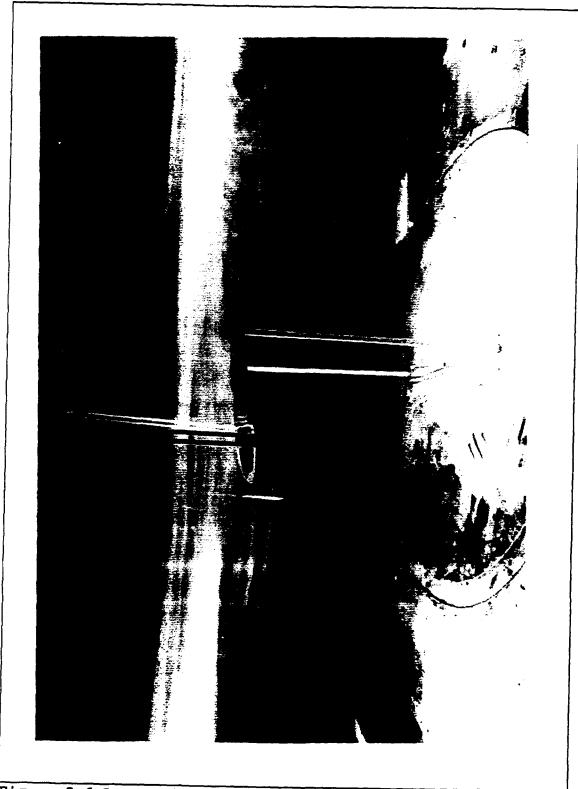


Figure 5.6 Large airfoil at 12 degrees AOA (stall)

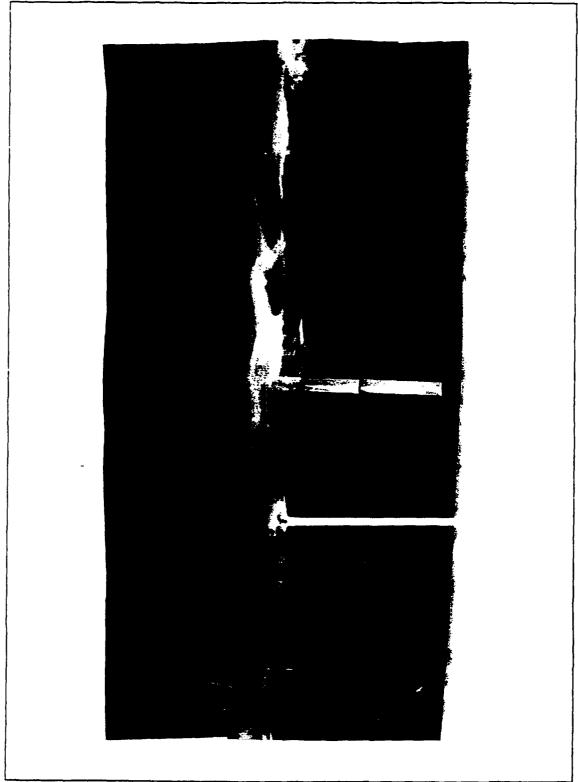


Figure 5.7 Plunge airfoil steady

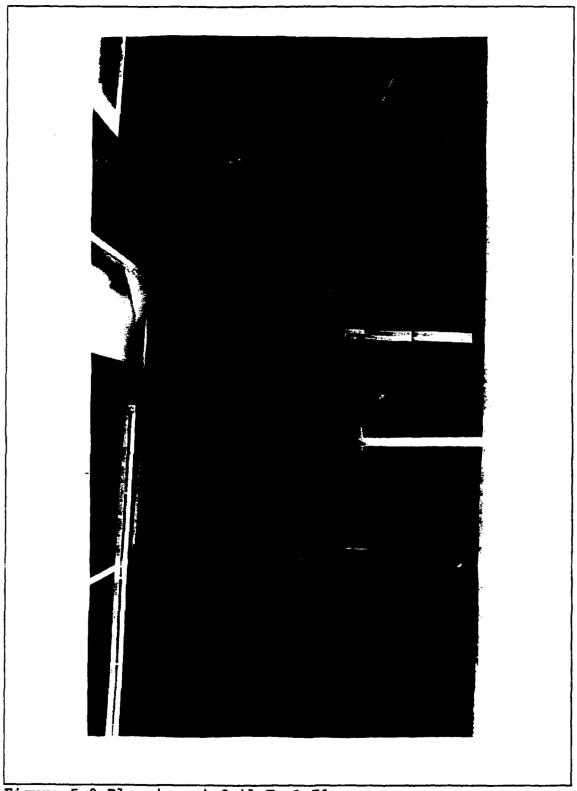


Figure 5.8 Plunging airfoil Kp=1.71

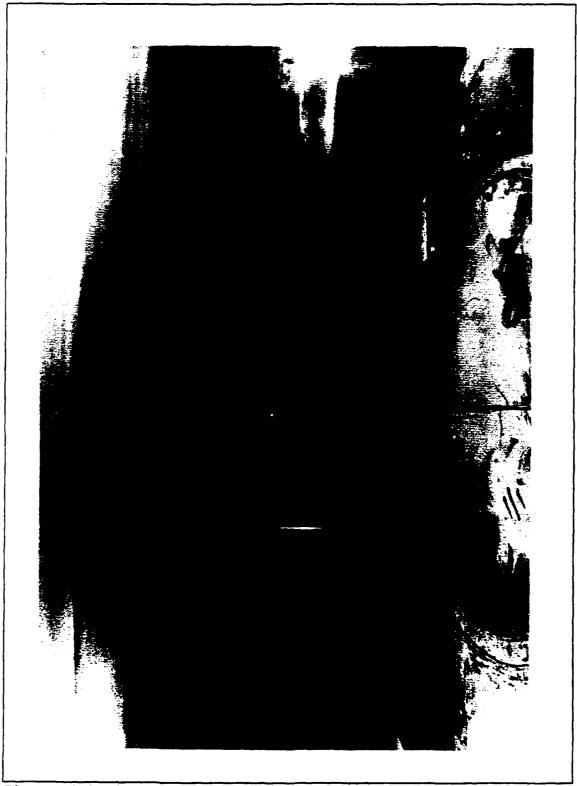


Figure 5.9 Plunging airfoil K_p=3.42

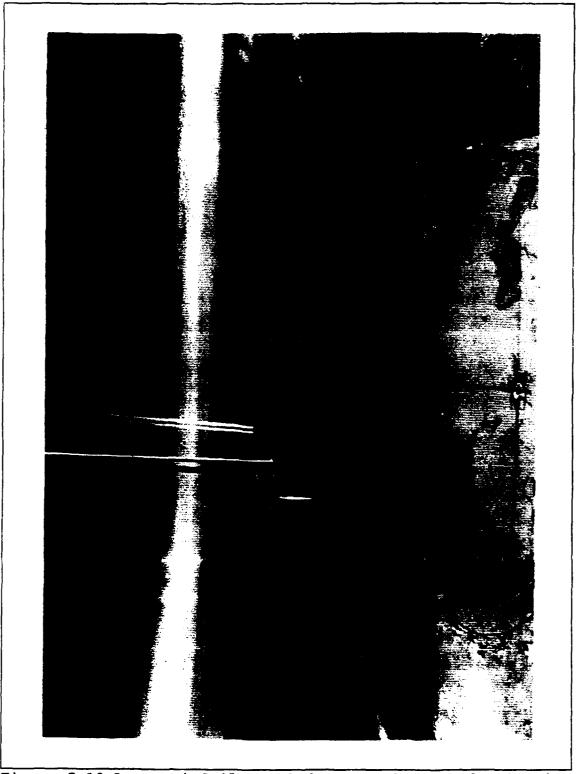


Figure 5.10 Large airfoil at 12 degrees AOA, steady plunging airfoil position 1

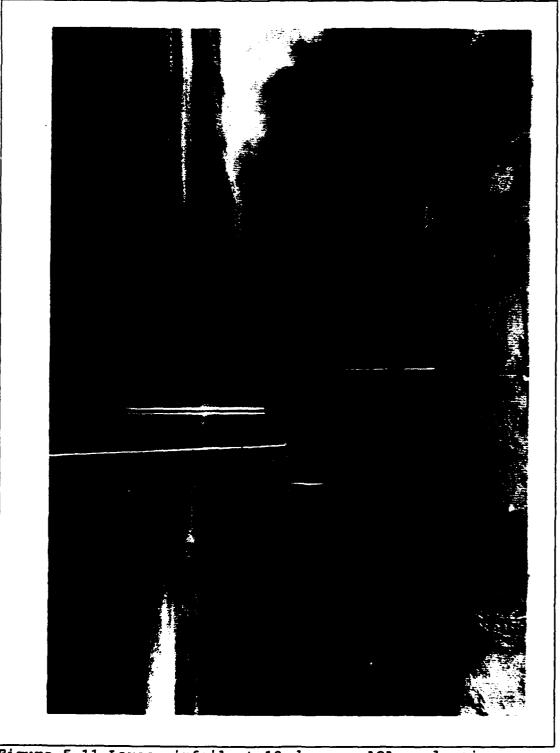


Figure 5.11 Large airfoil at 12 degrees AOA, plunging airfoil Kp=3.42, position 1

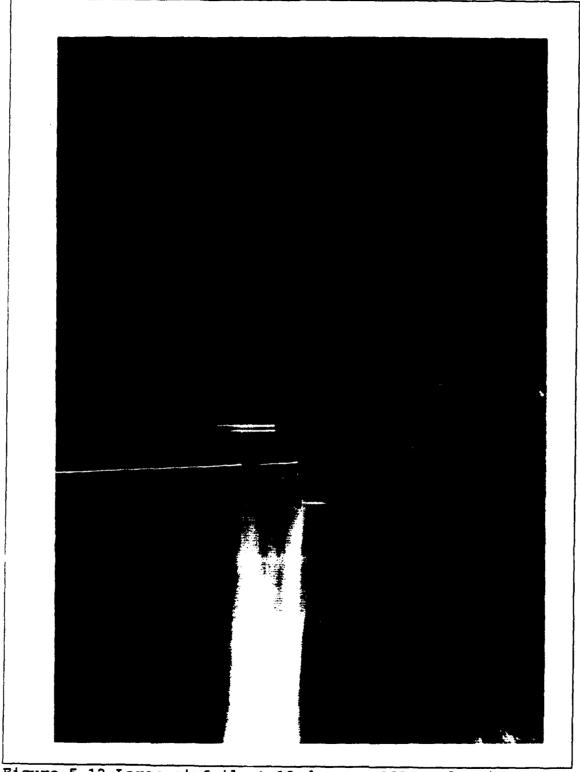


Figure 5.12 Large airfoil at 12 degrees AOA, plunging airfoil steady, position 2

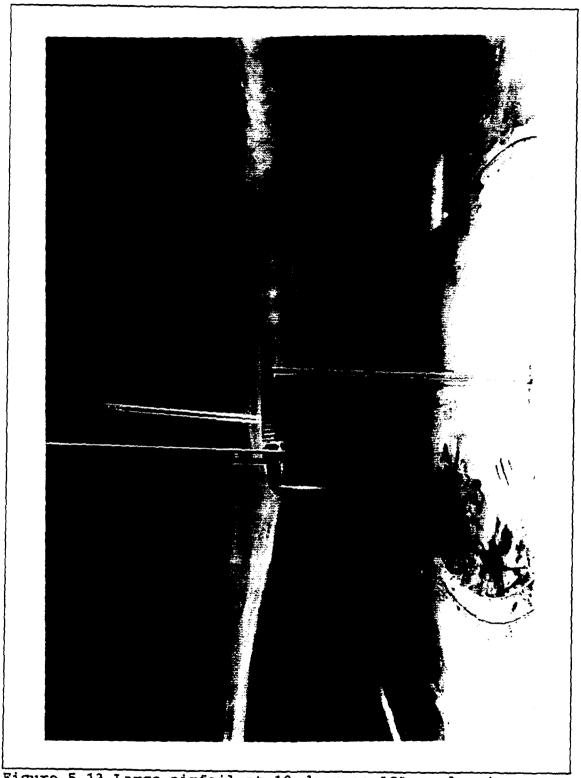


Figure 5.13 Large airfoil at 12 degrees AOA, plunging airfoil Kp=3.42, position 2

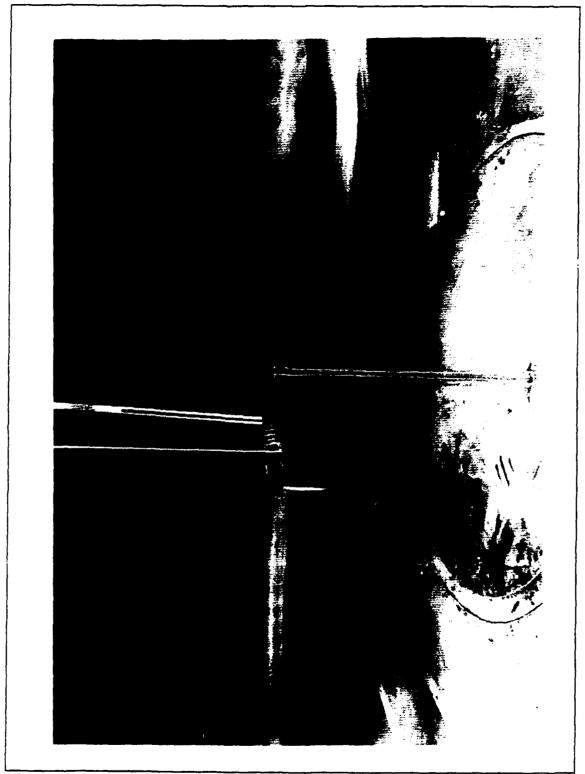


Figure 5.14 Large airfoil at 14 degrees AOA, plunging airfoil steady, position 2

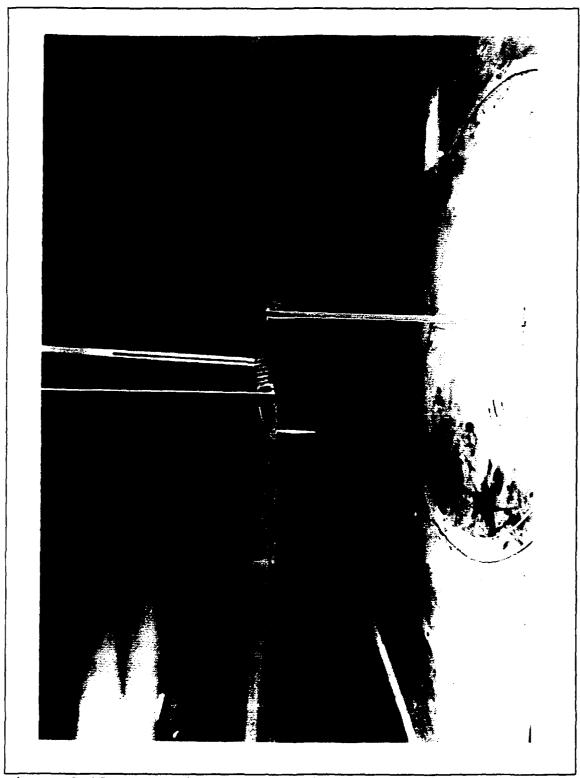


Figure 5.15 Large airfoil at 14 degrees AOA, plunging airfoil $K_p=3.42$, position 2

detailed investigation of the interference effects between the two airfoils.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. SINGLE AIRFOIL ANALYSIS

The modified version of U2DIIF (UPOT) can perform calculations over aerodynamic any range of reduced frequencies. The nonlinear theory presented here for harmonic motion, and the phase relationships that exist between the airfoil motion and the aerodynamic forces have been extensively verified by comparison with Theodorsen's linear theory. Furthermore, this panel code was applied to the analysis of incompressible bending-torsion airfoil flutter. Again, excellent agreement with the classical Theodorsen analysis was obtained.

Access to faster computational means is recommended to shorten the time needed to predict the flutter points. The code should be modified to incorporate three-dimensional calculations which would help solve more difficult flutter problems.

B. FLOW VISUALIZATION EXPERIMENTS

The flow visualization experiment successfully showed the development of thrust produced by a plunging airfoil. The enhanced lift experiment, on the other hand, was not a complete success. The smoke visualization presented difficulties that were not satisfactorily overcome. As a

result, the pictures taken were somewhat inconclusive. Futhermore, the angle of attack of the oscillating airfoil could not be changed thus making it difficult to achieve a flow condition conducive to lift enhancement.

It is recommended that further experiments be conducted in the low speed smoke tunnel with a shaker table capable of moving an airfoil at harmonic frequencies near 40 HZ. Additionally, the airfoil must be modified to allow change of AOA. Finally, the Rosco smoke machine output volume must be modified to permit much lower smoke output. This final point proved to be the single largest detriment to the visualization experiment.

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